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THE UNITED KINGDOM CONTRIBUTION TO THE AGARD 'FATIGUE-RATED FASTENER SYSTEMS' PROGRAMME

by

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SUMMARY

This Report describes an investigation of the relative merits of a number of fastener systems. They are termed 'fatigue-rated' fastener systems since they aim to enhance the fatigue endurance of the surrounding structure. Fatigue tests were performed on a number of laboratory specimens which simulated bolted connections in aircraft wing structures. It was shown that fastener systems incorporating hole cold expansion or fasteners installed with high interference fits were significantly superior to fasteners installed with a clearance fit in plain holes under the same test conditions. The longest fatigue endurances were observed in joints which contained fastener systems incorporating both cold expansion and a high degree of fastener interference. It was noted however, that cold expansion of fastener holes in asymmetric joints, with induced bending stresses, gave no increase in fatigue endurance over joints with fasteners installed in plain holes.

The work was carried out as part of an international collaborative exercise co-ordinated through the Structures and Materials Panel of AGARD.

Departmental Reference: Materials/Structures 259

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1 INTRODUCTION

The fatigue strength of metal structures is governed by the growth of cracks originated at points of local stress concentration. Probably the most common site of stress concentration in aircraft structure is at or near a fastener connection. In order to minimise related fatigue problems, a number of fatigue-resistant fastener systems have been evolved. These systems use one mechanism or a combination of mechanisms for fatigue life improvement of the material surrounding the hole; these are clamping, interference fit and cold expansion[1-5].

The main area of concern regarding fatigue of mechanically fastened joints in aircraft structures is the lower wing construction. This is because the lower wing experiences a tensile mean load in flight with gust and manoeuvre-induced loads superimposed. As a consequence, fatigue test specimens used to assess the performance of fastener systems must represent typical bolted connections occurring in this area. A connection along the span of the wing, *eg* skin to spar (span-wise), usually contains many fastener rows (see Fig 1) and the load transferred by any individual fastener row is small. In contrast, however, a connection across the chord of the wing, *eg* skin to rib (chord-wise), usually contains only two or three fastener rows, hence the load transferred by individual fastener rows is considerably higher[6]. There is therefore a wide variation in load transfer values encountered in practice.

The asymmetry of wing skin connections gives rise to bending stressess superimposed on the axial stresses in the joined components when the wing is subjected to loading. These are termed secondary bending stresses. Primary bending stresses are those produced by externally applied bending forces. As a consequence in aircraft structures a fastener connection may have a wide range of possible amounts of load transferred by the fastener and a range of secondary bending stresses[7]. To represent this range of possible values, a number of different laboratory test specimens have been designed in different establishments to determine the fatigue performance of some fatigue-rated fastener systems.

An AGARD SMP Sub-Committee was formed to assess the relative merits of fastener systems under representative loading conditions. This Report describes the UK contribution to the collaborative exercise agreed by the Sub-Committee.

2 THE AGARD "FATIGUE-RATED FASTENER SYSTEMS" PROGRAMME

The program outlined by the Sub-Committee[8] had the following objectives:

(a) to determine the fatigue lives of joints in different materials containing a range of fatigue-rated fastener systems in combination with hole preparation techniques and installation parameters,

(b) to establish the cost of the installed fastener systems and relate the cost to the fatigue performance,

(c) to identify the prime parameters involved in fastener system selection,

(d) to generate design data for a number of fastener systems tested under FALSTAFF loading,

(e) to develope a reference datum for the comparison of test results produced in different countries using different specimen geometries.

Each of the seven participating countries defined their own programme of work, but in order to fulfil objective (e), participants were also requested to perform a number of tests defined by core programmes to enable comparison of the test results.

The overall programme was split into four sections:

(i)	No-Load-Transfer Joints	(NLT)	
(ii)	Low-Load-Transfer Joints	(LLT)	
(iii)	Double-Shear Joints	(DS)	Both with high load transfer
(iv)	Single-Shear Joints	(SS)	

The NLT and LLT sections each had its own core programme. The UK were not involved in the no-load-transfer category but participated in the remaining three categories.

3 THE UK PROGRAMME

The UK participation involved the low-load-transfer (LLT) and double-shear (DS) categories as described in section 3.1, the low-load-transfer core programme (LLTC) as described in section 3.2 and the single-shear (SS) programme described in section 3.3.

The costing exercise required by the programme covered equipment and tooling, fasteners and hole preparation and installation costs calculated in terms of man hours. The installation details and costing were common for all the specimen types and are given in Appendix A which was prepared by British Aerospace (Warton). A summary of the costings (1982) is presented in Table 1. A recent similar exercise has been conducted which has shown that the fastener prices

have changed in relation to one another. The installation costs however have remained the same relative to one another. Since the installation costs are significantly greater than the fastener costs, the overall cost ranking of the systems has remained the same.

A standard requirement defined by the AGARD programme was that hole diameters should be measured for individual tests, to ensure that the fastener fit was constant for each fastener type. Hole diameters were measured for each specimen tested in the LLT and DS programmes only and are detailed in Tables 2 to 6. Holes A and B (referred to in the tables) are the two holes in each of the joint elements and correspond to fasteners 1 and 2 respectively as shown in the diagrams presented in Appendices B and C.

Another standard requirement defined by the AGARD programme was that all fracture surfaces should be examined to determine the failure modes. All specimens were examined and failure patterns (if any) were noted. A description of all the failure sites and failure patterns are given in Appendices B, C, D and E. These refer to the four categories, double shear, low-load-transfer, low-load-transfer core programme and single-shear respectively.

3.1 Low-load-transfer and double-shear programmes (LLT and DS)

The LLT and DS programmes described below constitute stage 3 of an extensive fastener evaluation programme being undertaken by RAE and BAe (see Table 7). Fatigue tests were performed on two types of specimen; the double-reversed-dog-bone (see Fig 2) for the LLT programme and the double-shear high-load-transfer joint (see Fig 3) for the DS programme. Both are described in section 4. Seven fastener systems were evaluated as described in section 5; namely:

Hi-Lok
Huck-Crimp
Hi-Tigue
Taper-Lok
FTI Split Sleeve (CX) and Hi-Lok
Acres Sleeve and Hi-Lok
Huck EXL.

The fatigue tests were performed under FALSTAFF loading as described in section 6.1.

3.2 Low-load-transfer core programme (LLTC)

The low-load-transfer joint used by the UK (Fig 2) in the LLT programme was a smaller version of the joint used by the other participating countries

(Fig 4). The UK joint was designed to overcome the buckling problems encountered by the AGARD LLTJ at high compressive stress levels under FALSTAFF loading. The UK joint was also of different plate material and was assembled with a different fastener material and different interfay compound to that used by the other participants. The low-load-transfer core programme was initiated to establish if there were any fundamental differences between the two types of joint which may give rise to differences in the fatigue performance of the fastener systems tested. In order to do this, it was necessary to assemble and test the larger AGARD joints using the fabrication methods, jointing compounds and fastener systems used by the UK in its LLT programme. Twenty joints (Fig 4) were fatigue tested in this part of the programme usi..g Hi-Lok fasteners, ten with and ten without cold expansion produced by the FTI split sleeve process.

3.3 Single-shear (high-load-transfer) programme (SS)

This part of the AGARD programme aimed to examine the behaviour of fastener systems in joints which had both high load transfer and high secondary bending. Each participant had to test their own joint design under a common set of assembly and testing conditions and from a common batch of material. The UK participation in this phase involved the fatigue testing of the recently developed "Q-JOINT" (see section 4). To make comparisons of the fatigue test results with those of other participants, it was necessary to know the degree of load transfer and secondary bending in each type of joint. It was therefore required for each participant to take measurements of load transfer and secondary bending. Accordingly strain gauged specimens (see Fig 5) were assembled and subjected to a load sequence, specified by the AGARD Sub-Committee[8], and the strain outputs were sampled using a mini-computer. From these measurements the load transfer and secondary bending values were calculated. A lot of strain gauge hysteresis was evident, as the movement in the joint had not stabilised. Consequently, the specimen was then "bedded-in" using a repeated loading of 0 to 30 kN for 20000 cycles and subjected again to the specified load sequence whilst measurements were taken.

4 FATIGUE TEST SPECIMENS

As described in section 1, a span-wise joint on the lower wing skin of an aircraft usually contains multiple fastener rows, each fastener transferring a small proportion of the total load transmitted by the complete connection. In order to represent this case, the low-load-transfer joint was designed to transfer about 5% of the total load. The UK specimen used in the LLT programme is

shown in Fig 2. The larger AGARD variant tested in the LLTC programme and described in section 3.2 is shown in Fig 4.

A chord-wise joint usually contains only two or three fastener rows. Consequently the load transferred by each fastener row is generally between one third and one half of the total load transferred. To represent this type of connection, the double-shear high-load-transfer joint was designed, each fastener transmitting about 50% of the total load. The specimen used in the DS programme was the double shear joint shown in Fig 3.

Strain gauge measurements have shown that high bending stresses do occur in aircraft structures due to the asymmetry of joint connections[7]. Such bending (secondary bending) should be differentiated from primary bending which is caused by the application of external forces. The secondary bending ratio in a joint is defined as the ratio of the bending strain at the interface to the gross nominal axial strain in the component (see Fig 6). Measurements on aircraft structures[7] show that the secondary bending ratio varies from 0 to 2 but the most commonly occurring values are between 0.3 and 0.7. Work on designing a specimen to model this situation has been continuing at RAE and the "Q-JOINT" used in the SS programme is the latest development (Fig 7).

The materials used for specimen manufacture were 7010-T7651 (DTD 5120) for the LLT and DS programmes and 7050-T76 for the LLTC and SS programmes. Mechanical and chemical properties of the two materials are given in Table 8. All specimens were "wet" assembled using Thiokol PR 1422A4 jointing compound.

5 FASTENER SYSTEMS

The seven fastener systems used in the LLT and DS programmes are described below. In the SS and LLTC programmes, only Hi-Lok fasteners were used in holes prepared with and without the FTI split sleeve cold expansion process. The fasteners used throughout were 6.35 mm diameter, with the exception of the fasteners used in the controlling section of the Q-joint (SS) (see Fig 7) which were 4.76 mm diameter. The fastener material used in the LLT and LLTC programmes was titanium and for the DS and SS programmes the material was steel.

Detailed descriptions of the fastener systems, installation procedures and costings are presented in Appendix A. The calculated values of percentage cold expansion and interference fit are presented in Appendix F. The following seven fastener systems were investigated:

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(a) Hi-Lok

The Hi-Lok fastener was chosen as the baseline system as it represents a commonly used clearance fit bolt. Hi-Loks may be assembled with clearance, or light interference fits. In this programme fasteners were installed with a clearance of 25 μm to 45 μm. Kaynar nuts were used in the LLT, LLTC and DS programmes, torque tightened to 6.8 to 9.1 Nm. In the SS programme Hi-Lok shear-off collars were used. The hexagonal nut part of the collar is designed to shear off when the required torque is achieved.

(b) Huck-Crimp

This fastener relies solely on clamping for the fatigue life improvement. After installation of the fastener, nuts were torque tightened to 7.5 Nm and then crimped onto the pin using the special tool supplied. The fastener was installed with a clearance fit of 12 μm to 48 μm.

(c) Hi-Tigue

The Hi-Tigue fastener is an interference fit fastener. The pin has conventional parallel sides of larger diameter than the hole but has a lubricated bead at the end; this expands the surrounding material as it is assembled, allowing the parallel pin to be drawn into the hole resulting in an interference fit. The pin must be installed using a rivet gun and then the nut assembled and tightened.

Hi-Tigue pins were assembled using an interference fit of between 100 μm and 120 μm. Kaynar nuts were used which were torque tightened to 10.2 to 11.3 Nm.

(d) Taper-Lok

Taper-Lok is an interference fit fastener employing a tapered fastener in a tapered hole. The fastener is inserted and then torque tightened to give the required interference. The torque settings used were 6.1 to 6.8 Nm in the LLT programme, and 10.9 to 12.7 Nm in the DS programme. The difference in torque values arises because of the different fastener material and different specimen thicknesses used. The interference in both specimen configurations was calculated to be between 43 μm and 100 μm.

(e) FTI Split Sleeve

The FTI Split Sleeve process cold expands fastener holes prior to fastener installation. A mandrel is inserted through the fastener hole and

a split sleeve passed over the mandrel, into the fastener hole. The mandrel is then pulled through the sleeve using a compressed air-powered puller or a manual puller. The sleeve is then discarded and any further hole preparation (*ie* ream, countersink) can take place.

Holes prepared in this way resulted in a cold expansion of between 3% and 5%. The holes were given a final ream to the required size. Hi-Lok fasteners were then installed with Kaynar nuts and torque tightened to 6.8 to 9.1 Nm. The fastener was installed with an interference fit of 8 μm to 25 μm.

(f) Acres Sleeve

This process is similar to the FTI process except that a solid sleeve is used which remains in place after the mandrel has been drawn through. No further finishing processes are used.

The installation of Acres Sleeves resulted in cold expansion of between 3.4% and 4.7%. Hi-Lok fasteners were then installed with a transition fit in the range 12.5μm clearance to 12.5 μm interference. Kaynar nuts were assembled and torque tightened to 6.8 to 9.1 Nm.

(g) Huck EXL

This fastener combines all three fatigue life improvement mechanisms. It is a two part fastener pin, the first part cold expands the hole as it is drawn through, and the second part is a parallel sided interference fit fastener. When installed, a collar is placed over the grooves of the pin and crimped whilst the first part of the pin is pulled to provide the clamping force. The first part eventually breaks off when the increasing applied tensile load reaches the material UTS and the installation is complete.

These fasteners produced between 1.2% and 4.2% cold expansion, with 90 μm to 150 μm interference.

6 FATIGUE TESTS

The fatigue testing was carried out at two different sites; the LLT and DS programmes at BAe (Woodford), as described in section 6.1, and the SS and LLTC programmes at RAE (Farnborough), as described in section 6.2.

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6.1 Low-load-transfer and double-shear programmes (LLT and DS)

The testing was carried out on Mayes 100 kN electro-hydraulic fatigue machines. Five test specimens per condition were used. The loading sequence used was FALSTAFF applied at two different stress levels, at a constant rate of loading. In the LLT programme the load levels were chosen to give net section stresses of 280 MPa and 350 MPa at FALSTAFF level 32. For the DS programme the net section stresses were 280 MPa and 375 MPa. The mean cyclic frequency was 11 Hz giving a frequency of 1.8 Hz for the maximum load excursion. All testing was continued until complete separation of the joints had occurred.

6.2 Single-shear and low-load-transfer core programmes (SS and LLTC)

Testing of joints in the SS and LLTC programmes was carried out using Dowty 200 kN electro-hydraulic fatigue machines. Five test specimens per condition were used. The loading sequence was FALSTAFF again at two different stress levels. The net sections stress levels for both programmes were 280 MPa and 350 MPa at FALSTAFF level 32. The mean cyclic frequency was 27.1 Hz giving a maximum load excursion frequency of 4.4 Hz. The increase in testing frequency in these tests compared to those described in section 6.1 is not expected to affect the overall fatigue endurance of the joints.

7 RESULTS AND DISCUSSION

7.1 Low-load-transfer and double-shear programmes (LLT and DS)

The fatigue test results obtained in the LLT and DS programmes are given in Tables 9 and 10 respectively. They are summarised in Table 12 which gives the relative life improvement factors over the plain Hi-Lok system. With the exception of the Huck-Crimp system used in the LLT programme, significant life improvements were gained by using life-enhancing fastener systems. The probable reason for the failure of the Huck-Crimp to increase the fatigue life over the base Hi-Lok system is that improved clamping has little effect in low-load-transfer situations. Since only 5% of the load is transferred through the fastener connection, reducing this 5% by an alternative load path will probably not significantly affect the fatigue life. In contrast however in the high-load-transfer joint used in the DS programme, where some 50% of the load is transferred by the fastener connection, clamping alone can significantly improve fatigue performance by providing a load path which bypasses the fastener. Hence, all the fatigue-rated fastener systems exhibit an improvement over the base Hi-Lok system in the high load transfer joint.

Examining next the effect of interference fit alone, it should be remembered that the fastener systems other than Hi-Lok, Huck-Crimp and Acres sleeve rely to some degree on interference fit. Hi-Lok and Huck-Crimp fasteners are installed in clearance fit holes whilst the Acres sleeve system uses a transition fit fastener and does not therefore rely on an interference fit. The Taper-Lok system is a pure interference fit fastener. The Hi-Tigue system can also be considered to be a pure interference fit fastener, although the bead at the threaded end of the fastener must cold expand the hole to some extent as it is drawn through. The bead however is only some 5 μm larger in diameter than the fastener shank, which is installed with an average interference of 110 μm. The tangential residual stress field around the fastener after installation will be very little different (if at all) from a pure interference fit situation. Both of these systems (Hi-Tigue and Taper-Lok) produce significant improvements in fatigue life over the datum system (Table 11). The improvements are greater at the higher applied stress level and also generally greater in the DS joints. It should be remembered that steel fasteners were used in the DS joints and titanium in the LLT joints. The higher modulus steel fasteners result in a lower stress concentration at the fastener hole and a greater depth of plastically deformed material following installation. As a consequence, steel fasteners in an interference fit situation are generally superior in fatigue performance to titanium fasteners. This may partly explain the greater improvements in the DS joints.

The three remaining systems, FTI split-sleeve, Acres sleeve and Huck-EXL all rely on cold expansion. As mentioned in the previous paragraph they are also all installed with some degree of interference fit (Acres sleeve is a transition fit). The degree of interference is very low for the two sleeve systems, but the Huck-EXL system has a high interference fit. The two sleeve systems can therefore be considered to represent the case of cold working only. As can be seen from Table 11, significant life improvements are gained when comparing the basic Hi-Lok system with the two sleeve methods. As with the interference fit fasteners, the life improvements are greater at the higher stress level. The split sleeve system gives greater life improvement in the DS joints than in the LLT joints. This is probably because steel fasteners were used in the DS joints and titanium in the LLT joints, as discussed earlier for interference fit systems. In contrast however the solid sleeve process shows similar life improvements in both types of joint; the reason for this behaviour is not understood.

The final system, the Huck EXL, gives the greatest life improvement of all the systems tested. This result may be expected since this system relies on

both cold expansion and interference fit. The Huck-EXL system once again shows greater life improvements at the higher stress levels, and greater life improvements in the DS joints, compared to the LLT joints, for the same reasons as described earlier.

These results enable direct comparison of fastener systems to be made but care should be taken when trying to predict potential life improvements in practical situations. Fatigue lives will be dependent on the material both of the fastener and of the joint. The stress-strain characteristics of the joint material determine the effectiveness of cold expansion as they control the magnitude of the resulting residual stress distribution. Changing the fastener material alters the fastener flexibility which has a significant effect on fatigue life, as studied extensively by Huth[9]. The fastener material also affects the stress concentration with interference fit fasteners and the depth of plastically deformed material, which will in turn affect the fatigue endurance. Changing the fastener fits, degrees of cold working, etc, have similarly been shown in the present work to affect the fatigue performance. Extreme care should therefore be exercised when choosing a fastener system, and the fatigue results should be assessed in conjunction with the costings detailed in Appendix A.

7.2 Low-load-transfer core programme (LLTC)

The fatigue test results for the low-load-transfer AGARD specimen tested in the LLTC programme are given in Table 12 and are shown in Fig 8 along with the results of the UK joint tested in the LLT programme. Whilst the results are very similar it should be noted that the life improvement due to cold working is greater in the AGARD joint than in the UK joint. This is partly due to the reduced edge margin in the UK joint. It is noticeable from the fracture surface examinations detailed in Appendices D and E that the specimens which were cold expanded have different failure modes. The UK joints failed from fretting origins away from the bore of the hole whilst the AGARD joints failed from origins at the bore of the hole. The UK joint is therefore less affected by the cold expansion process since the crack originates away from the area of maximum beneficial residual stress.

7.3 Single-shear (high-load-transfer) joint programme (SS)

The fatigue test results of the SS programme are given in Table 13. It is clear from these results that expected life increases due to cold expansion do not occur. The measurements of load transfer and secondary bending described in section 3.2 are presented in Table 14. The load transfer is similar for both

plain and cold expanded holes. Despite the bedding-in process described in section 3.2 the strain gauges measuring the load transfer still exhibit a large hysteresis. This has the effect of giving an apparent increase in load transfer when unloading the specimen from peak FALSTAFF load to zero load. The secondary bending values are also similar for plain and cold worked holes, giving a secondary bending ratio of about 0.44 at the peak applied load. This means that the surface strains at the joint interface where cracks initiate are 44% higher than the axially applied strains. As a consequence, at both of the applied stress levels significant yielding occurred at the fastener holes when the high loads in the FALSTAFF spectrum were applied. From these measurements and the fatigue test lives, it is concluded that this yielding caused by the high secondary bending is the dominant factor in the failure process. From an examination of the fracture surfaces (Appendix E) it was observed that at the higher applied stress level failures occurred through the centre line of the fasteners in both plain and cold expanded holes. The origins were predominantly from the intersection of the edge of the fastener hole and the faying surface. It is concluded that the beneficial compressive residual stresses caused by the cold expansion process are of the same order as those induced by the high secondary bending across the centreline of the fastener in the test section.

At the lower stress level it was observed that failures did not occur across the minimum section, in contrast to the observed behaviour at the high stress level. Failures in the plain hole specimens occurred across a line approximately tangential to the edge of the fasteners and origins were predominantly away from the fastener hole (see Appendix E). Failures in the cold expanded specimens were further displaced from the test-sections with origins predominantly towards the centre or edges of the specimen. For both plain and cold expanded hole specimens, failures were therefore away from the locations where beneficial compressive residual stresses would be induced; this may account for similar fatigue endurances at the lower stress level.

8 CONCLUSIONS

(1) Symmetrical double-shear high-load-transfer joints assembled with fastener systems employing the mechansims of clamping, interference fit and cold expansion gave improved fatigue performance over those assembled with the datum Hi-Lok system. The life improvements based on log mean lives ranged from 2 to 15 times the lives of the datum fastener joints.

(2) Low-load-transfer joints assembled with fastener systems employing the mechanisms of interference fit and cold expansion gave improved fatigue performance

over those assembled with the datum Hi-Lok system. The life improvements based on log mean lives ranged from 2 to 4 times the lives of the datum fastener joints.

(3) Fatigue life improvements were more marked at higher stress levels. For the test conditions investigated in this programme the improvement at the highest stress level was between 1/20 and 3 times that at the lower stress level, but typically 1½ to 2 times.

(4) No fatigue improvement was gained by cold-expanding fastener holes in specimens with large amounts of secondary bending and high-load-transfer.

(5) A fastener system employing both cold expanison and interference fit gave the best overall fatigue performance in both low-load-transfer and symmetrical high-load-transfer joints.

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Appendix A

FASTENER SYSTEMS, INSTALLATION PROCEDURES AND COSTS

A.1 Introduction

This Appendix describes the seven fastener systems used in the programmes, installation details, and costs (1982 prices) are included. Costs are discussed in section A.2 and installation procedures and considerations are discussed in section A.4.

A.2 Discussion of costing excercise

Table A1 details the hole preparation tooling, installation tooling and inspection gauge requirements for each fastener system and gives the relative tool cost in each case. Costs of standard tools, *ie* drills, reamers, plug gauges, torque spanners, etc, are not included. Fastener costs are based on titanium fasteners and are the cost per 100 pieces assuming an order of 5000. The cost of steel fasteners are not included but are generally of the same order as the titanium fasteners. All costings given are relevant to the time of specimen assembly in 1982.

Full production assembly techniques could not be applied to the relatively small number of fasteners to be installed. For this reason, it was considered that to give actual assembly times for the specimens would be misleading. However, estimated assembly time ratios of each fastener relative to that of the datum fastener, Hi-Lok in plain hole, are given. They are based on experience gained during assembly of specimens with, in some cases, previous use of the system. In addition, an estimate is given for the installation, including hole preparation of one hundred fasteners. This is based on BAe Warton assembly times for 6.0 mm Hi-Lok fasteners. A brief description of each system, assembly procedure and observations made during assembly of the specimens are given in the following paragraphs A.3 and A.4.

A.3 Description of fastener systems

Hi-Lok (in plain hole) - Fig A.1

The normal Hi-Lok system consists of two parts, a threaded pin which contains a hexagon recess in the threaded end, and a threaded collar. The collar contains a hexagon driving portion which shears off at a groove to provide a consistent torque and bolt pre-load. The Hi-Lok pin used in the LLT and DS programmes has a K-Fast nut, instead of the collar described above, which is self-locking and can be re-torqued or re-used if necessary.

Huck-Crimp (Fig A.2)

The Huck-Crimp fastener system consists of a threaded pin and free running nut. Pre-load is transmitted to the pin by torque-tightening the nut. The nut is then crimped (squeezed) using a power-tool, to provide a lock. In addition, this crimping action is claimed to increase the pin preload and hence the joint clamping pressure. After crimping, the correct amount of crimp is verified by applying a special gauge.

Hi-Tigue (Fig A.3)

The Hi-Tigue pin is almost identical to the Hi-Lok pin except that it contains a slight "bead" at the threaded end of the shank. The "bead" is of slightly greater diameter than the shank of the bolt, and both are lubricated. The "bead" allows much lower installation loads to be used and also work-hardens the hole surface.

The Hi-Tigue pin was assembled with a K-Fast nut in this test programme.

Taper-Lok (Fig A.4)

The Taper-Lok system consists of a threaded taper shank bolt (1 in 48 taper), a washer nut assembly, and various hole preparation tools and gauges.

During installation, the bolt is pulled until seated into an interference fit tapered hole by torqueing the washer-nut. The amount of interference is directly proportional to the protrusion of the bolt before being pulled completely into the hole. This protrusion/interference is measured using a special gauge.

FTI split sleeve (with Hi-Lok)(Fig A.5)

This system provides cold expansion of the fastener hole by radially expanding the hole using a hardened steel tapered mandrel which is drawn through a pre-lubricated steel sleeve.

After the hole has been cold expanded the sleeve is discarded and the hole finally reamed as required. The amount of cold expansion can be varied by adjusting the starting hole diameter. Oversize sleeves are available for cold expanding existing holes.

Acres sleeve (with Hi-Lok) (Fig A.6)

This is a similar process to the FTI split sleeve method, except that the sleeve (not split as the FTI) is left in the hole after cold expansion. This is followed by installation of the relevant fastener. Final reaming is not necessary.

The amount of cold expansion can be varied by using various combinations of mandrel and starting hole diameter. Intermediate sizes are covered by a range of oversize sleeves.

Huck-EXL (Fig A.7)

The Huck-EXL system consists of a pin and swaging collar. Part of the pin contains a spherical portion which cold expands the hole as it is pulled into it. Whilst pulling the pin, via labyrinth grooves at the pin tail, the collar is swaged into locking grooves and, as the tension load increases, the pin breaks at a reduced portion. The operation is carried out by using a special Huck pulling tool.

The fastener system used in this programme is, in fact, a simulation of the EXL system in that a Huck GP pin is used in conjunction with a separate mandrel to provide the cold expansion. This is due to the high cost of the titanium pulling portion which would have to be thrown away once the fastener is set. The same collar as EXL is used and the same pulling tool.

A.4 Installation procedures/comments

Hi-Lok (in plain hole)

Fastener holes were prepared and after applying the sealing compound to the specimen the pin was inserted by hand into the hole until seated. In order to torque-tighten the K-fast nut, to 6.8 to 9.1 Nm as required, it was necessary to manufacture a special adaptor. This allowed the hexagon key to engage the slot in the pin whilst applying the torque.

Application of this adaptor proved to be a tedious operation, particularly when overcoming the friction lock of the nut. For full production use, a torque controlled power-tool would have to be used. The option of hand installation can present an advantage when fasteners are required to be set in areas with different access. Standard "off the shelf" sockets will not fit the K-fast nuts, so a Kaynar special socket must be used.

Huck-Crimp

Fastener holes were prepared and after applying sealing compound to specimen elements the pin was placed, by hand, into the hole. The nut was then engaged on to the pin, torque tightened and then crimped with the Huck crimping tool. The amount of "crimp" was checked by using a special Huck gauge.

Since the pin is installed into a clearance hole it is not necessary to use a riveting gun. The nut is free running, so it can be spun up to the structure face by hand.

Good access is essential for application of the power crimping tool. Crimping cannot be carried out by hand and there are no right angled tools available. Once the nut has been crimped, further torqueing, if required, is not possible.

Hi-Tigue

Fastener holes were produced to dimensions given in Appendix F and the bolt was inserted into the hole and seated using a riveting gun. Prior to this, sealing compound was inserted in the specimen elements. It was also necessary to ensure that the specimen was securely clamped and supported. K-fast nuts were then assembled and torque tightened using a special adaptor similar to that applied to the Hi-Loks.

Care had to be taken that the riveting gun did not damage either the head of the bolt or the face of the specimen. Similar precautions would need to be taken if this technique is used on structure. It is also necessary to have firm support for the structure and secure clamping to prevent distortion and opening of the structure sheets. Some areas may not have sufficient access to the head for a riveting gun.

The application of the special adaptor again proved to be a tedious operation and, as with the Hi-Loks, a power-tool with torque control would need to be used for full production use. Since the Hi-Tigue is installed with interference fit, application of a power-tool would be simple because the bolt would not tend to push back when the nose piece was applied.

Taper-Lok

Pilot holes were "deburred" at the interface in order to prevent breakdown of the specimens after final taper reaming. The correct size of deburr was measured by first drilling and reaming in a representative piece of scrap material. Final taper reaming was carried out using a Briles cage and taper reamer. For final finishing of the taper hole a "Duplex" hand reamer was applied. Each hole was checked for correct fastener bearing by applying a "blueing" gauge and holes were periodically checked using a countersink depth gauge and hole diameter checking gauge. The Taperlok bolt was pulled down until seated by torqueing the nut after first checking for correct pin protrusion. When seated the nut was torque tightened to requirements of BAe Warton standards.

A large percentage of time/cost is taken in preparing the taper hole which requires the use of the expensive taper reamers and gauges. In addition, special precautions must be taken to ensure that the structure is securely clamped together, by slave bolting, prior to the taper reaming operation. It is essential that the structure is not disturbed once the final taper-reamed hole is produced. Checking of the hole for bearing area is a time consuming but essential operation, particularly in multilayer structures of different materials.

All the aforementioned operations must be closely controlled and carried out by skilled personnel.

<u>FTI split sleeve (with Hi-Lok)</u>

Fastener holes were prepared and then cold expanded using the correct mandrel, split sleeve and pulling equipment. Care was taken to ensure that the specimen was adequately clamped and that the sleeve was positioned with the split along the length of the specimen. After discarding the sleeve, the hole was examined for evidence of the ridge left by the sleeve and for confirmation of the minimum "after cold work" diameter. The holes were then finally reamed and the Hi-Lok fastener fitted as detailed in section A.3.

Good access is required for the large puller gun and space must be available for the separate intensifier which uses a conventional compressed air supply to produce a high pressure oil supply to the puller gun. To assist with any access problems a puller gun with an offset nose and a right-angled puller gun are available. There is also a hand tool available for the smaller diameters.

<u>Acres sleeve (with Hi-Lok)</u>

Fastener holes were prepared and sealing compound applied to specimen elements. They were then cold expanded by placing the sleeve, which was fitted on the mandrel, into the hole from the countersink side and activating the pulling tool to draw the mandrel through the sleeve. The sleeve was left in position in the hole and Hi-Lok fasteners were installed as detailed in section 3.

The feature of leaving the sleeve, at final hole size, in the hole after cold expansion initially appears to present an advantage over the FTI Split Sleeve system. However, difficulties were encountered during installation of the sleeves. Many of the unused sleeves were difficult to push on to the mandrel and after cold expanding some sleeves were found to be standing proud of the specimen while others had deformed heads.

Removal of the deformed sleeves with a punch proved to be a very difficult operation since great care had to be taken not to damage the hole with the punch. The latter was found either to enter the sleeve or distort it and it was therefore necessary to remove them by drilling from the head side using a drill of slightly smaller diameter than that of the hole.

Since the difference in diameter between the smallest Hi-Lok pin head and the largest sleeve head can be almost 150 μm, it was found difficult to achieve the flushness required for the specimen. This could increase hole preparation time in areas requiring a close tolerance aerodynamic flushness.

The mandrel must be removed from the pulling tool for each application of a sleeve and good access is essential at the head side of the sleeve since no reduced access tooling, *ie* right angled or off set, is available. The large pulling tool requires at least four operations of the trigger to pull the mandrel through the sleeve.

Consideration must be given to the increase in weight due to the sleeve being left in the hole and the difficulties involved in dis-assembly of structure, if required, for refurbishment or repair.

<u>Huck-EXL (GP)</u>

After preparing the hole to the required size, the hole was cold expanded by pulling a separate mandrel through the hole using the Huck pulling tool. The GP pins were installed into the hole by a riveting gun after first applying sealing compound to the specimens. Collars were swaged into position using the Huck swaging tool.

The EXL fastener can be installed in one continuous operation, *ie* the hole cold expanded by the land on the integral pulling portion, the pin pulled into the hole and the collar swaged on to the pin. With the simulated version, these operations must be carried out separately which increases the installation time. However, the EXL is not available in titanium because of the high fastener cost.

The GP pin is available either as a "stump" version, *ie* without the pulling portion, or as a "pull type" with the pulling portion. Although the stump version is cheaper, care must be taken to ensure that the structure is tightly clamped or service bolted. The pull type automatically pulls the structure sheets together when operating the installation tool. Sufficient access is needed from both sides of the structure to accommodate a riveting gun at the head side or the swaging/pulling tool at the tail side.

In addition to the standard straight pulling/swaging tool, smaller right angled tools are available to assist installation in areas of difficult access.

Table A.1

FASTENER INSTALLATION COSTS

	Hole preparation		Installation tooling	Preparation costs				Estimated fastener installation time ratios	Estimated time per 100 fastener (hours)
	Tools	Inspection gauges		'Special' installation tools	Special hole preparation tools	Special inspection gauges	Fastener cost (per 5000 U.O.S. Exc. NUT/COL)		
Hi-Lok (in plain hole).	Standard drill and reamer.	Plug gauge.	Standard torque spanner and allen key (Ref section A.4) Special Socket for K fast nut.	£755 [1] -	-	-	£112 per 100	1.0 datum	8.7
Huck-Crimp.	Standard drill and reamer.	Plug gauge + 1.Crimping gauge.	Standard torque spanner and socket. Huck crimping tool.	£422	-	£13	£54 per 100	1.4	12.2
Hi-Tigue.	Standard drill and reamer.	Plug gauge.	Standard riveting gun, torque spanner and socket.	£755 [1]	-	-	£127 per 100	1.1	9.6
Taper-Lok.	Standard drill. + 1.Taper reamer 2.Cage.	Plug gauge. + 1.Blueing G. 2.Hole sizing G. 3.CSK depth G. 4.Protrusion G.	Standard torque. Spanner and socket.	-	1.£135 2.£100	1.- 2.£420 3.£135 4.£9	£258 per 100	5.0	43.5
Hi-Lok in FTI split sleeve cold WK.hole.	Standard drill and reamer + 1.Split sleeve 2.Mandrel 3.Puller unit and gun.	Plug Gauge (2 off).	Standard torque spanner and allen key.	£775 [1]	- 1.£0.46 [2] each 2.£59 each 3. £2,330	-	£112 per 100 (Hi-Lok). £4.60 per 100 (Sleeve) [2]	2.0	17.4
Hi-Lok in acres sleeve cold WK.hole	Standard drill and reamer.	Plug gauge (2 off).	Standard torque spanner and allen key + 1.Pulling tool 2.Special mandrel	£775 [1] 1.£765 2.£14	-	-	£112 per 100 (Hi-Lok) £28 per 100 (Sleeve)	1.6	13.1
Huck EXL.	Standard drill and reamer + 1.Mandrel 2.Puller gun.	Plug gauge (2 off)	Huck pulling and swaging tool. Standard riveting gun.	£401	1. [3] 2.As inst. tool.	-	£50 per 100 (GP pin)	1.4	12.2

[1] Approx power tool cost [2] Based on order of 100 - £0.46 each [3] Negligible cost

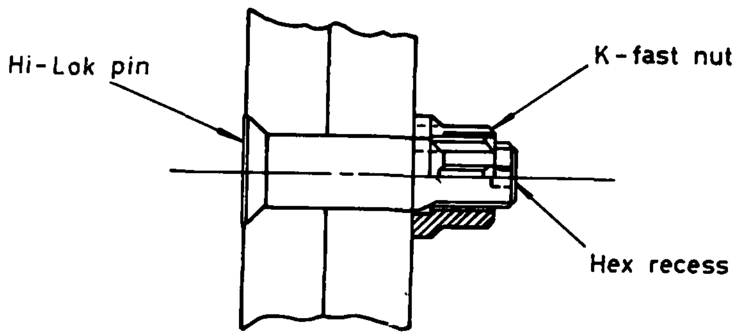

Fig A1 Hi-Lok

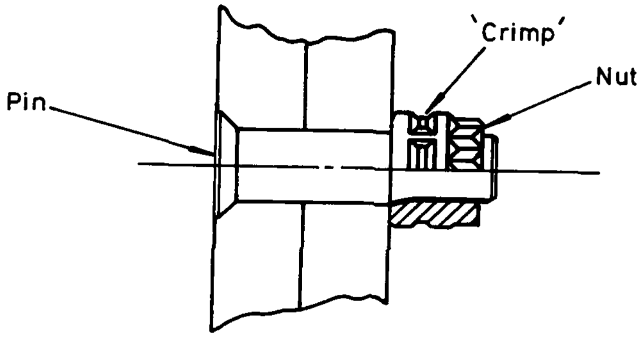

Fig A2 Huck-crimp

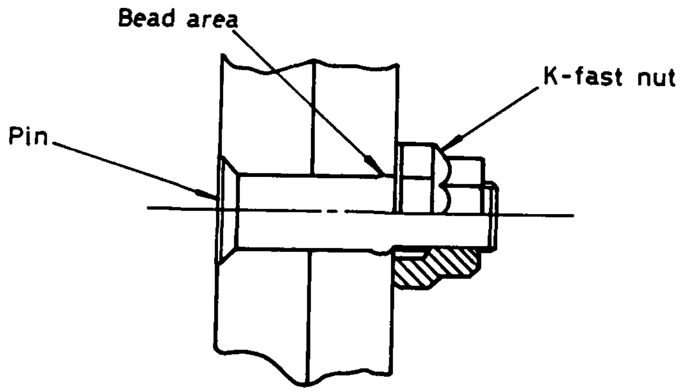

Fig A3 Hi-Tigue

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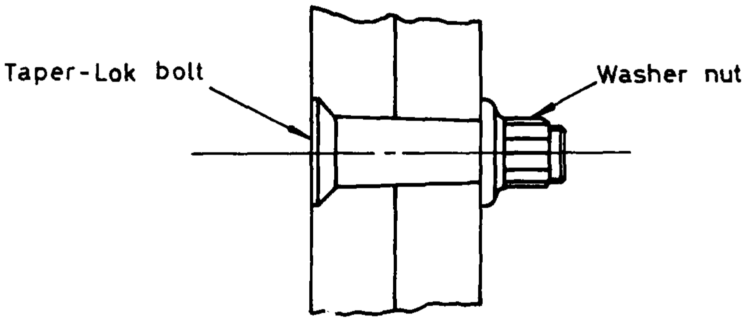

Fig A4 Taper-Lok

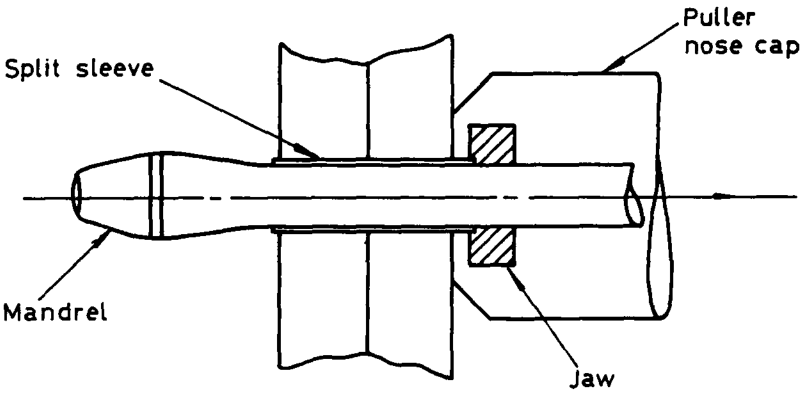

Fig A5 FT I split sleeve

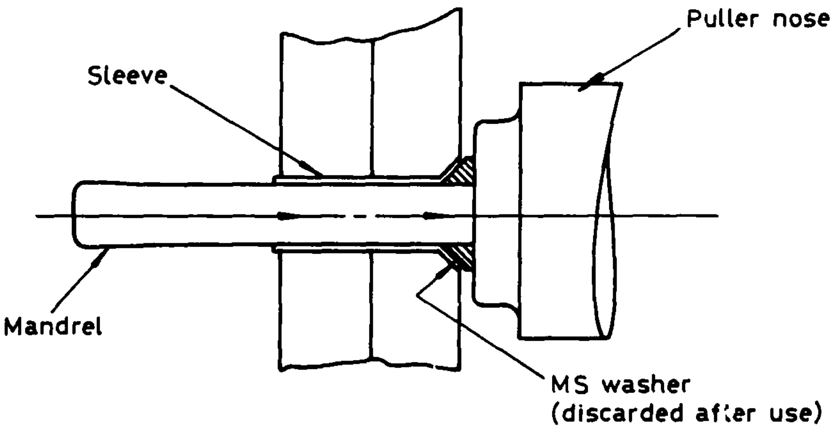

Fig A6 Acres sleeve

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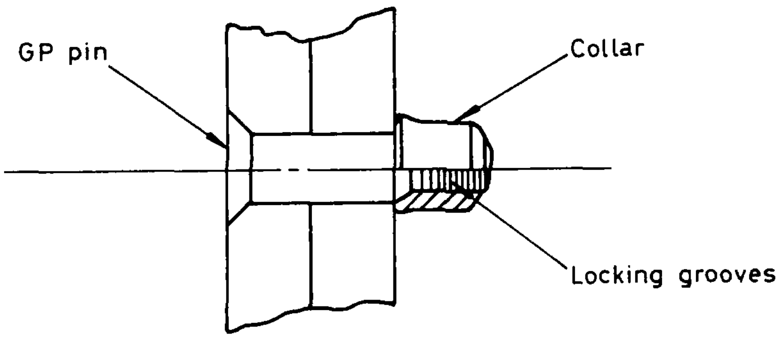

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Fig A7 Huck EXL

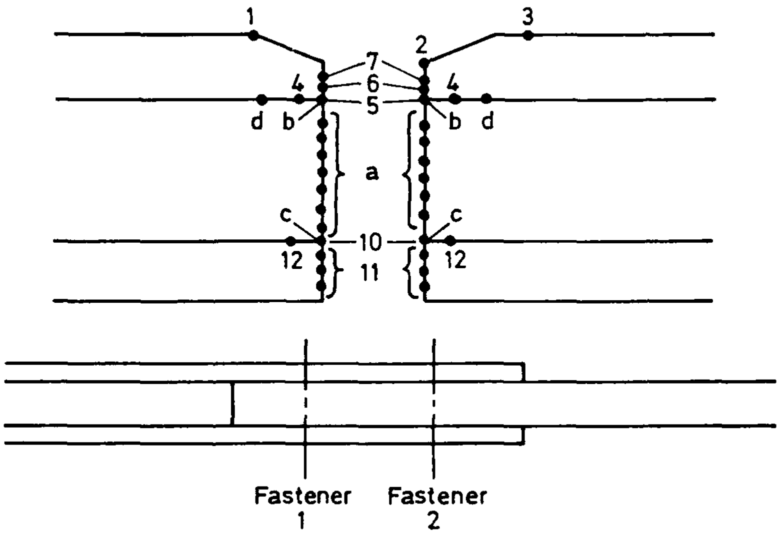
Appendix B

PRIMARY FATIGUE CRACK ORIGINS - DS PROGRAMME

Primary fatigue crack origins were noted for each fatigue test specimen and are presented in this Appendix.

High-load-transfer specimens (DS)

Top plate - origins 1-7
Centre plate - origins a-d
Bottom plate - origins 10-12



Fastener system	Maximum net stress (MPa)	Spec. No.	Flights to failure	Origins
(a) Hi-Lok in plain hole	280	H1/1	37898	4
	280	H1/6	23172	10
	280	H1/5	30839	a
	280	H1/10	34929	c
	280	H1/7	14821	10
	375	H1/2	7572	a
	375	H1/9	4031	a
	375	H1/8	3559	a
	375	H1/3	3431	a
	375	H1/4	2959	5,6,7,11
(b) Taper Lok	280	H2/3	172929	6
	280	H2/1	91211	d,a
	280	H2/9	191085	NA
	280	H2/7	134759	2,7
	375	H2/8	21421	5
	375	H2/2	42929	1,4
	375	H2/10	29206	5
	375	H2/4	47772	b,c
(c) Huck-EXL	280	H3/9	211711	d,12
	280	H3/1	155031	b
	280	H3/3	155172	b
	280	H3/4	96996	d
	280	H3/5	146572	d
	375	H3/6	87511	b
	375	H3/7	58880	10
	375	H3/8	55172	c
	375	H3/10	59929	b
	375	H3/2	52972	10
(d) Hi-Tigue	280	H4/2	66624	-
	280	H4/5	32796	b
	280	H4/7	52172	10
	280	H4/9	123227	6,7
	280	H4/10	41024	b
	375	H4/1	34224	10
	375	H4/3	27749	10
	375	H4/4	27031	10
	375	H4/6	12972	6,7
	375	H4/8	20924	6,7

Fastener system	Maximum net stress (MPa)	Spec. No.	Flights to failure	Origins
(e) Huck Crimp	280	H5/7	50911	11,13
	280	H5/3	14825	11,13
	280	H5/8	45274	11
	280	H5/2	143431	11
	280	H5/6	114529	6
	375	H5/1	18943	11,10
	375	H5/5	14329	10,11
	375	H5/10	17031	11
	375	H5/4	20572	NA
	375	H5/9	19524	11
(f) FTI split-sleeve and Hi-Lok	280	H6/2	51172	11
	280	H6/8	76759	11
	280	H6/4	>224420	-
	280	H6/1	166196	11
	280	H6/9	93021	11
	375	H6/7	31759	11
	375	H6/3	34525	11
	375	H6/6	27772	5
	375	H6/10	27359	6,7
(g) Acres sleeve and Hi-Lok	280	H7/2	124759	NA
	280	H7/6	41929	13
	280	H7/7	45635	NA
	375	H7/10	13624	10
	375	H7/4	9031	11
	375	H7/5	16972	NA
	375	H7/3	12329	11
	375	H7/12	30621	NA

Observations:

1) Failures in the top and bottom plates originate at fastener 1.

2) Failures in the centre plate originate at fastener 2.

3) The majority of failures using system (c) are in the centre plate, the longest lives are achieved with this system.

4) The majority of failures using system (d) are in the side plates.

5) All of the failures using system (e) are in the side plates, the majority are in the bottom plate.

6) All of the failures using system (f) are in the side plates, the majority in the bottom plate.

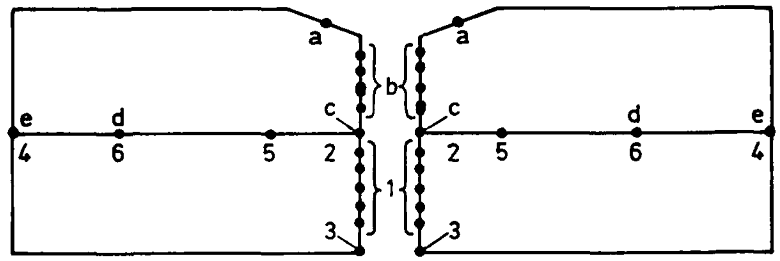
7) Of the specimens available using system (g), all failed in the bottom plate.

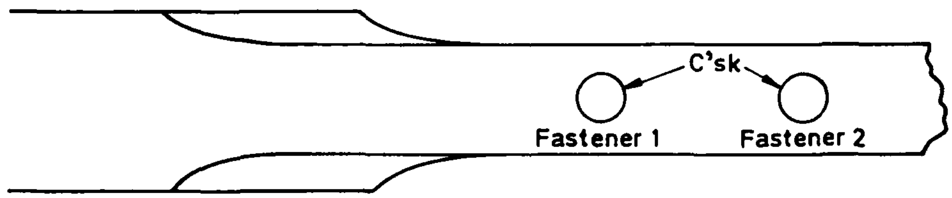
Appendix C

PRIMARY FATIGUE CRACK ORIGINS - LLT PROGRAMME

Primary fatigue crack origins were noted for each fatigue test specimen and are presented in this Appendix.

Low-load-transfer specimens (LLT)





Fastener system	Maximum net stress (MPa)	Spec. No.	Flights to failure	Origins[1]
(a) Hi-Lok in plain hole	280	L1/11	25231	(1)b
	280	L1/12	12372	(2)1,b
	280	L1/13	21359	(2)1,b
	280	L1/14	19292	(1)1(2)c
	350	L1/4	6631	(2)b,1
	350	L1/5	5711	(2)b,1
	350	CL/1	4929	NA
(b) Taperlok	280	L2/6	54231	(1)6,1
	280	L2/7	37772	a
	280	L2/3	50631	(2)a
	280	L2/8	24831	(2)a,b
	280	L2/10	27863	(1)a
	350	L2/2	22972	(1)5
	350	L2/4	30796	(1)5(2)d
	350	L2/1	14224	(1)a,b
	350	L2/9	27172	a,5
	350	L2/5	26811	NA
(c) Huck EXL	280	L3/1	27531	(1)2,1
	280	L3/2	80280	REM(1)2
	280	L3/4	120272	(1)1
	280	L3/6	39759	(1)5,1
	280	L3/7	36431	(1)1
	350	L3/3	14224	(1)5
	350	L3/5	20631	(1)5(2)d
	350	L3/8	26490	(1)5,1
	350	L3/9	39111	(1)NA
	350	L3/10	24205	(1)a,5
(d) Hi-Tigue	280	L4/1	55351	(2)a
	280	L4/9	54772	(1)a
	280	L4/4	53172	(1)5(2)a
	280	L4/7	42172	(1)a
	280	L4/10	74772	(2)a(1)a
	350	L4/6	17080	(1)a,b
	350	L4/3	17729	(2)a
	350	L4/8	22959	(1)a
	350	L4/5	21572	(1)5,a
	350	L4/2	23372	(1)a

1 Origins are described by fastener number in parentheses followed by locations as shown in the above diagram.
REH denotes failure remote from fastener hole.

Fastener system	Maximum net stress (MPa)	Spec. No.	Flights to failure	Origins
(e) Huck Crimp	280	L5/3	12929	(1)2,1
	280	L5/4	10724	(1)2(2)b
	280	L5/6	13172	(2)1,b
	280	L5/7	11011	(2)2,1,c
	280	L5/5	18959	(1)2,1(2)c
	350	L5/1	5280	(1)1(2)c
	350	L5/2	5698	(1)1
	350	L5/8	6128	(1)1
	350	L5/9	5024	(2)1,b
	350	L5/10	5024	(1)1(2)b
(f) FTI Split-sleeve and Hi-Lok	280	L6/2	72372	(2)d,b
	280	L6/3	87172	(2)e
	280	L6/5	40529	(1)5,1
	280	L6/6	43372	(2)d,e
	280	L6/8	60572	(1)4,1
	350	L6/1	14725	(1)1(2)e,b
	350	L6/7	20711	NA
	350	L6/4	18031	(1)4(2)c
	350	L6/10	23359	(1)d(2)1
	350	L6/9	16559	(1)d,b
(g) Acres sleeve and Hi-Lok	280	L7/4	54625	(2)c,b
	280	L7/5	34372	REMOTE
	280	L7/6	60511	(2)b,a
	280	L7/7	38231	(2)b
	280	L7/9	44231	(2)d
	350	L7/1	19372	(2)b
	350	L7/2	17031	(2)e,b
	350	L7/3	21231	(1)d,b
	350	L7/8	22989	(2)d,b,1
	350	L7/10	19972	(1)6(2)c

Observations:

1) Failures with the two clamping only systems (a) and (e) originated from multiple points along the bores of both plates.

2) All of the specimens with system (d) had cracks originating at the countersink, three also had interface cracks.

3) All of the specimens with system (b) had cracks originating from the countersink or the interface.

046

4) Failures with the two interference fit systems (b) and (d) always originated from the countersink or the interface.

5) All specimens with system (f) had cracks originating at the interface, generally away from the system hole.

6) Most specimens with system (g) had multiple cracks originating from the bore of the countersink hole, generally at hole 2.

7) Specimens tested with system (g) at the higher stress level and two specimens at the lower stress level exhibited interface cracking with at least one origin away from the fastener hole.

8) Specimens tested with system (c) at the higher stress level and two specimens at the lower stress level exhibited interface cracking.

9) All specimens tested with system (c) failed at fastener hole 1.

10) A general observation is that the majority of failures occur in the following places:

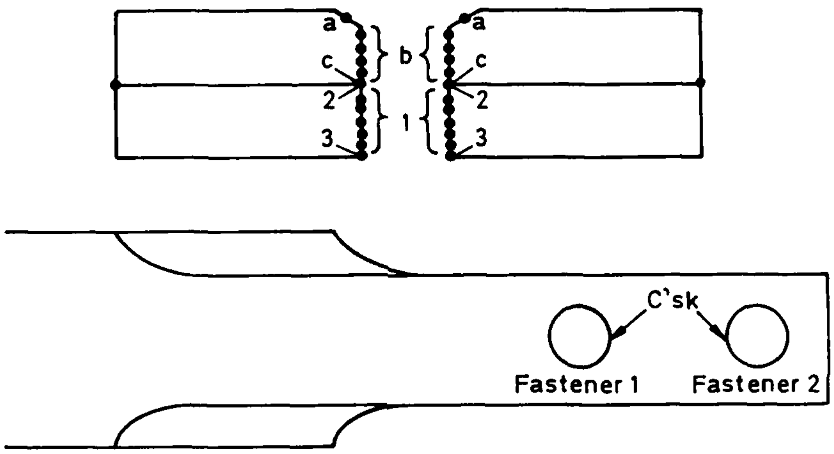
  (a) clearance fit plain holes - multiple bore origins,
  (b) interference fit plain holes - countersink,
  (c) cold worked holes - specimen interface after remote from fastener hole.

Appendix D

PRIMARY FATIGUE CRACK ORIGINS - LLTC PROGRAMME

Primary fatigue crack origins were noted on each fatigue test specimen and are presented in this Appendix.

AGARD low-load-transfer specimens (LLTC)



Fastener system	Maximum net stress (MPa)	Spec. No.	Flights to failure	Origins[1]
(a) Hi-lok in plain hole	280	A2	26337	(2)b,1
	280	A4	19972	(1)1,c
	280	A8	21724	(2)b,1
	280	A9	24129	(1)b,1
	280	A10	23172	(2)c,1
	350	A1	6221	(1)1,b
	350	A5	7031	(2)1,b
	350	A6	6011	(1)1,b
	350	A7	4480	(1)1,b
	350	A11	4729	(1)1,b
(b) FTI split sleeve and Hi-lok	280	CW2	136464	Grip Failure
	280	CW3	173572	Grip+(2)1
	280	CW7	50759	(2)c,d(1)1
	280	CW8	178745	(2)a,c,2,1
	280	CW9	240231	(1)1,2
	350	CW1	19172	(1)1
	350	CW4	33880	Remote
	350	CW5	32031	(1)1
	350	CW6	22329	(2)c,b,a
	350	CW10	39824	(1)1,b

1 Origins are described by fastener number in parentheses followed by location as shown in the above diagram.

Observations

1) With fastener system (a), all cracks have multiple origins in the non-countersink plate and either multiple bore or single corner interface origins in the countersink plate.

2) With fastener system (b) all specimens had multiple cracking in one plate with a variety at other origins.

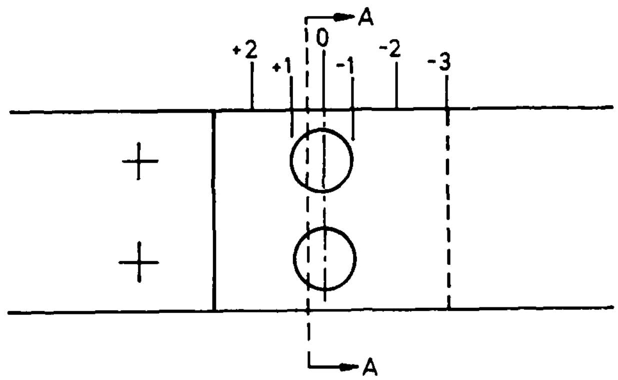
3) One specimen, CW4, failed from a site remote from the test section.

Appendix E

PRIMARY FATIGUE CRACK ORIGINS - SS PROGRAMME

Primary fatigue crack origins were noted for each fatigue test specimen and are presented in this Appendix.

Q-joint specimens (SS)



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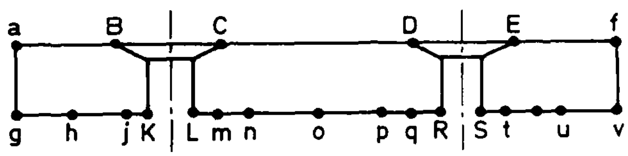


Fastener system	Maximum net stress (MPa)	Spec. No.	Flights to failure	Origins[1]
(a) Hi-lok in plain hole	280	X3	12128	(-1)j,m,q,t
	280	X4	14431	(-1)h,m,q,t
	280	X7	12160	(-1)m,q(0)S
	280	X9	13831	(-1)j,m,q,t
	280	X10	14031	(-1)j,q,t
	350	X1	3925	(-1)m,t
	350	X2	2929	(0)K,L,R,S
	350	X5	3444	(0)K,L,R,S
	350	X6	4336	(0)K,L,R,S
	350			
(b) FTI split sleeve and Hi-lok	280	CW2	9631	(-2)g,(-1)n
	280	CW4	14424	(-2)o,p
	280	CW6	12329	(-1.5)(0)K
	280	CW9	16224	(-1.5)h,q,u
	280	CW10	17631	(-1)j,m,p,t,u
	350	CW3	3801	(0)K,L,q,S
	350	CW5	3172	(0)K,L,S
	350	CW7	3624	(0)K,L,R
	350	CW8	5323	(0)K,L,R,(-1)o,u

1 Origins are described by displacement from the centre line of the fasteners in the test section which are given in parentheses, followed by cross sectional locations as shown in the above diagram.

Observations

1) At the higher applied stress level with both fastener systems, seven of the eight specimens tested failed across the minimum section from cracks originating at the interface of the hole and the faying surfaces.

2) At the lower applied stress with both fastener systems, all of the specimens failed away from the minimum section. In the case of plain hole specimens origins were approximately on a line tangential to the edge of the fastener and slightly away from the fastener hole. In the case of cold worked specimens origins were generally further away from the fastener holes, some cracks propagated back to the fastener holes and some propagated across the gross section away from the fastener holes.

Appendix F

CALCULATIONS OF PERCENTAGE COLD EXPANSION AND INTERFERENCE FIT

This Appendix presents the calculations of percentage cold expansion and interference fit of the fastener systems. The calculations are made based on the diameters of the mandrels, sleeves and fasteners assuming them to be perfectly rigid. The minimum cold expansion is therefore calculated using the minimum mandrel/sleeve combination diameter and the maximum initial hole diameter. The maximum cold expansion is calculated using the maximum mandrel/sleeve combination diameter with the minimum initial hole diameter. Calculations of minimum and maximum interference fit use the same principle, substituting fastener diameter for mandrel/sleeve combination diameter. The dimensions used throughout are in inches, since all measurements were made using the Imperial system.

(a) Hi-Tigue

Pin diameter = 0.2490 min

= 0.2495 max

Hole diameter = 0.2445 min

= 0.2460 max

Minimum interference (%)
$$= \frac{\text{Min Pin} - \text{Max Hole}}{\text{Max Hole}} \times 100$$
$$= \frac{0.2490 - 0.2460}{0.2460} \times 100$$
$$= \boxed{1.22\%}$$

Maximum interference (%)
$$= \frac{\text{Max Pin} - \text{Min Hole}}{\text{Min Hole}} \times 100$$
$$= \frac{0.2495 - 0.2445}{0.2445} \times 100$$
$$= \boxed{2.04\%}$$

(b) Taper-Lok

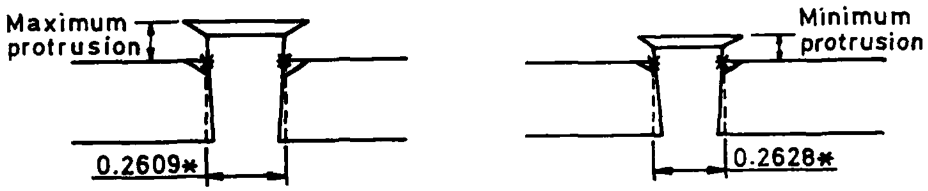
$$\left.\begin{array}{ll}\text{Max interference} & = 0.0042 \\ \text{Min interference} & = 0.0018\end{array}\right\} \text{From Taper-Lok literature}$$

Maximum interference (%)
$$= \frac{0.0042}{0.2592} \times 100 = \boxed{1.62\%}$$

(Based on Reamer Gauge diameter of 0.2592)

Minimum interference (%)
$$= \frac{0.0018}{0.2592} \times 100 = \boxed{0.69\%}.$$

Note: More accurate calculations, based on the diameter at the test piece surface for maximum and minimum interference/ protrusion, may be carried out as shown below.



* - (Obtained from further calculation).

Then maximum interference (%) $= \frac{0.0042}{0.2609} \times 100 = \boxed{1.61\%}$

and minimum interference (%) $= \frac{0.0018}{0.2628} \times 100 = \boxed{0.68\%}$.

The values are practically the same as that based on the gauge dimension only, because the taper is slight (1 in 48).

(c) <u>FTI split sleeve</u>

Start hole diameter	= 0.235 min
	= 0.238 max
Mandrel diameter	= 0.2298 min
	= 0.2308 max
Sleeve thickness	= 0.0076 min
	= 0.0084 max

$$\text{Minimum cold expansion (\%)} = \frac{\text{Min Mandrel Diameter} + 2\ (\text{Min sleeve thickness}) - \text{max start hole diameter}}{\text{Max start hole diameter}} \times 100$$

$$= \frac{0.2298 + 2\ (0.0076) - 0.238}{0.238} \times 100$$

$$= \boxed{2.94\%}$$

Maximum cold expansion (%) $= \dfrac{\text{Max Mandrel Diameter} + 2\ (\text{Max sleeve Thickness}) - \text{Min start hole diameter}}{\text{Min start hole diameter}} \times 100$

$= \dfrac{0.2302 + 2\ (0.0084) - 0.235}{0.235} \times 100$

$= \boxed{5.1\%}$.

Hi-Lok pin diameter = 0.2490 min

= 0.2495 max

Final reamed hole diameter = 0.248 min

= 0.249 max

Minimum interference (%) $= \dfrac{\text{Min pin diameter} - \text{Max final hole diameter}}{\text{Max final hole diameter}} \times 100$

$= \dfrac{0.2490 - 0.2490}{0.2490} \times 100$

$= \boxed{0\%}$

Maximum interference (%) $= \dfrac{\text{Max pin diameter} - \text{Min final hole diameter}}{\text{Min final hole diameter}} \times 100$

$= \dfrac{0.2495 - 0.248}{0.248} \times 100$

$= \boxed{0.6\%}$

(d) Acres sleeves

Mandrel size = 0.2528 min

= 0.2532 max

Sleeve thickness = 0.008 min

= 0.009 max

Starting hole diameter = 0.259 min

= 0.260 max

Minimum cold expansion (%) $= \dfrac{\text{Min Mandrel diameter} + 2\ (\text{Min sleeve thickness}) - \text{Max starting hole diameter}}{\text{Max starting hole diameter}} \times 100$

$= \dfrac{0.2528 + 2\ (0.008) - 0.260}{0.260} \times 100$

$= \boxed{3.38\%}$

Maximum cold expansion (%) $= \dfrac{\text{Max Mandrel diameter} + 2\ (\text{Max sleeve thickness}) - \text{Min starting hole diameter}}{\text{Min starting hole diameter}} \times 100$

$= \dfrac{0.2532 + 2\ (0.009) - 0.259}{0.259} \times 100$

$= \boxed{4.71\%}$

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(e) Huck EXL

Pin diameter	= 0.2485 min
	= 0.2495 max
Start hole diameter	= 0.238 min
	= 0.243 max
Mandrel diameter	= 0.246 min
	= 0.248 max

Minimum cold expansion (%)

$$= \frac{\text{Min Mandrel diameter} - \text{Max hole diameter}}{\text{Max hole diameter}} \times 100$$

$$= \frac{0.246 - 0.243}{0.243} \times 100$$

$$= \boxed{1.23\%}$$

Maximum cold expansion (%)

$$= \frac{0.248 - 0.238}{0.238} \times 100$$

$$= \boxed{4.2\%}$$

Hole diameter after cold expansion = 0.244 min

= 0.247 max

Minimum interference (%)

$$= \frac{\text{Min pin diameter} - \text{Max hole diameter}}{\text{Max hole diameter}} \times 100$$

$$= \frac{0.2485 - 0.247}{0.247} \times 100$$

$$= \boxed{0.6\%}$$

Maximum interference (%)

$$= \frac{\text{Max pin diameter} - \text{Min hole diameter}}{\text{Min hole diameter}} \times 100$$

$$= \frac{0.2495 - 0.244}{0.244} \times 100$$

$$= \boxed{2.26\%}$$

Summary

Cold expansion	- FTI split sleeve	2.94% - 5.1%
	- Acres sleeve	3.38% - 4.71%
	- Huck EXL	1.23% - 4.2%
Interference fit	- Hi-Tigue	1.22% - 2.04%
	- Taper Lok	0.68% - 1.61%
	- FTI split sleeve	0 - 0.6%
	- Huck EXL	0.6% - 2.26%

Table 1

RELATIVE COST OF THE FASTENER SYSTEMS (1982 PRICES)

	Cost of equipment and tools (£)	Cost of 100 fasteners (£)	Man hour cost of installation of 100 fasteners (£)	Total cost of 100 fasteners and their installation (£)
Hi-Lok Plain hole	755	112	161	273
Huckcrimp	435	54	226	280
Hi-Tigue	775	127	178	305
Taper Lok	800	258	805	1063
FTI split sleeve	3164	117 including sleeves	322	439
Acres sleeve	1554	140 including sleeves	243	383
Huck-EXL	400	50	226	276

Table 2

HOLE DIAMETER MEASUREMENTS - HI-LOK AND HUCK-CRIMP SYSTEMS

(a) Fastener type - Hi-Lok in plain holes

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L1/11	6.368	6.363	H1/1	6.365	6.365
L2/12	6.363	6.365	H1/2	6.365	6.365
L1/13	6.363	6.368	H1/3	6.365	6.365
L1/14	6.365	6.365	H1/4	6.368	6.365
			H1/5	6.368	6.368
L1/4	6.368	6.368	H1/6	6.365	6.365
L1/5	6.368	6.368	H1/7	6.365	6.365
CL 1	6.368	6.368	H1/8	6.365	6.365
			H1/9	6.365	6.368
			H1/10	6.365	6.368

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Table 2 (concluded)

(b) Fastener type - Huck-crimp

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L5/1	6.368	6.368	H5/1	6.368	6.365
L5/2	6.368	6.368	H5/2	6.368	6.368
L5/3	6.365	6.368	H5/3	6.368	6.368
L5/4	6.370	6.368	H5/4	6.368	6.368
L5/5	6.370	6.368	H5/5	6.368	6.368
L5/6	6.370	6.365	H5/6	6.368	6.368
L5/7	6.363	6.365	H5/7	6.368	6.368
L5/8	6.363	6.365	H5/8	6.368	6.365
L5/9	6.368	6.368	H5/9	6.365	6.365
L5/10	6.368	6.368	H5/10	6.365	6.368

Table 3

HOLE DIAMETER MEASUREMENTS - HI-TIGUE SYSTEM
FASTENER TYPE -HI-TIGUE

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L4/1	6.218	6.218	H4/1	6.218	6.223
L4/2	6.218	6.220	H4/2	6.220	6.220
L4/3	6.220	6.220	H4/3	6.220	6.218
L4/4	6.218	6.218	H4/4	6.223	6.220
L4/5	6.218	6.220	H4/5	6.223	6.223
L4/6	6.223	6.223	H4/6	6.228	6.228
L4/7	6.218	6.218	H4/7	6.228	6.228
L4/8	6.218	6.218	H4/8	6.228	6.223
L4/9	6.220	6.220	H4/9	6.223	6.228
L4/10	6.223	6.223	H4/10	6.223	6.225

Table 4

HOLE DIAMETER MEASUREMENTS - FTI SPLIT SYSTEM
FASTENER TYPE - FTI SPLIT SLEEVE SYSTEM AND HI-LOK

(a) Before cold expansion

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L6/1	6.020	6.020	H6/1	6.020	6.020
L6/2	6.020	6.020	H6/2	6.020	6.020
L6/3	5.994	5.994	H6/3	6.020	6.020
L6/4	5.994	5.994	H6/4	6.020	6.020
L6/5	5.994	6.020	H6/5	6.020	5.994
L6/6	6.020	6.020	H6/6	6.020	5.994
L6/7	5.994	6.020	H6/7	6.020	5.994
L6/8	5.994	6.020	H6/8	6.020	6.020
L6/9	5.994	6.020	H6/9	6.020	6.020
L6/10	5.994	6.020	H6/10	6.020	6.020

Table 4 (continued)

(b) After cold expansion

Low load transfer (LLT)			High load transfer DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L6/1	6.147	6.172	H6/1	6.121	6.121
L6/2	6.147	6.147	H6/2	6.147	6.147
L6/3	6.172	6.147	H6/3	6.147	6.172
L6/4	6.147	6.147	H6/4	6.147	6.172
L6/5	6.147	[illegible]147	H6/5	6.147	6.147
L6/6	6.147	6.147	H6/6	6.147	6.147
L6/7	6.172	6.147	H6/7	6.147	6.147
L6/8	6.147	6.147	H6/8	6.147	6.147
L6/9	6.147	6.147	H6/9	6.147	6.147
L6/10	6.147	6.147	H6/10	6.147	6.147

Table 4 (concluded)

(c) Final size

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L6/1	6.312	6.314	H6/1	6.314	6.312
L6/2	6.314	6.317	H6/2	6.317	6.314
L6/3	6.314	6.312	H6/3	6.317	6.314
L6/4	6.312	6.314	H6/4	6.314	6.314
L6/5	6.312	6.317	H6/5	6.314	6.314
L6/6	6.312	6.317	H6/6	6.314	6.314
L6/7	6.312	6.317	H6/7	6.314	6.314
L6/8	6.312	6.317	H6/8	6.314	6.314
L6/9	6.312	6.317	H6/9	6.314	6.317
L6/10	6.312	6.312	H6/10	6.314	6.314

Table 5

HOLE DIAMETER MEASUREMENTS - ACRES SLEEVE SYSTEM
FASTENER TYPE - ACRES SLEEVE AND HI-LOK

(a) Before cold expansion

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L7/1	6.604	6.594	H7/1	6.591	6.589
L7/2	6.591	6.599	H7/2	6.591	6.589
L7/3	6.594	6.591	H7/3	6.591	6.589
L7/4	6.594	6.591	H7/4	6.591	6.589
L7/5	6.594	6.591	H7/5	6.591	6.594
L7/6	6.589	6.591	H7/6	6.591	6.594
L7/7	6.589	6.591	H7/7	6.589	6.591
L7/8	6.589	6.599	H7/8	6.589	6.591
L7/9	6.589	6.599	H7/9	6.589	6.591
L7/10	6.589	6.599	H7/10	6.589	6.591

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Table 5 (concluded)

(b) After cold expansion

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L7/1	6.274	6.274	H7/1	6.299	6.299
L7/2	6.299	6.274	H7/2	6.299	6.299
L7/3	6.274	6.274	H7/3	6.299	6.299
L7/4	6.274	6.274	H7/4	6.299	6.299
L7/5	6.274	6.274	H7/5	6.299	6.274
L7/6	6.274	6.299	H7/6	6.299	6.274
L7/7	6.274	6.299	H7/7	6.299	6.299
L7/8	6.274	6.299	H7/8	6.299	6.299
L7/9	6.274	6.299	H7/9	6.299	6.299
L7/10	6.274	6.299	H7/10	6.299	6.299

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Table 6

HOLE DIAMETER MEASUREMENTS - HUCK-EXL SYSTEM
FASTENER TYPE - HUCK-EXL

(a) Before cold expansion

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L3/1	6.096	6.096	H3/1	6.096	6.096
L3/2	6.071	6.096	H3/2	6.096	6.096
L3/3	6.096	6.096	H3/3	6.096	6.096
L3/4	6.096	6.096	H3/4	6.096	6.096
L3/5	6.096	6.096	H3/5	6.096	6.096
L3/6	6.096	6.096	H3/6	6.096	6.096
L3/7	6.096	6.096	H3/7	6.096	6.096
L3/8	6.096	6.096	H3/8	6.096	6.096
L3/9	6.096	6.096	H3/9	6.096	6.096
L4/10	6.096	6.096	H3/10	6.096	6.096

Table 6 (concluded)

(b) After cold expansion

Low load transfer (LLT)			High load transfer (DS)		
	Hole dia. (mm)			Hole dia. (mm)	
Spec No.	Hole A	Hole B	Spec No.	Hole A	Hole B
L3/1	6.223	6.223	H3/1	6.248	6.248
L3/2	6.223	6.223	H3/2	6.248	6.248
L3/3	6.198	6.198	H3/3	6.248	6.223
L3/4	6.172	6.198	H3/4	6.248	6.248
L3/5	6.196	6.198	H3/5	6.248	6.223
L3/6	6.248	6.248	H3/6	6.274	6.223
L3/7	6.223	6.223	H3/7	6.223	6.248
L3/8	6.223	6.172	H3/8	6.248	6.248
L3/9	6.223	6.196	H3/9	6.274	6.248
L3/10	6.223	6.248	H3/10	6.248	6.248

Table 7

EVALUATION OF FATIGUE RESISTANT FASTENERS:
OUTLINE OF RAE/BAe PROGRAMME

Chronological stage number	Purpose	Activity
Stage 1	Selection of fastener types.	Paper study of possible fastener for evaluation.
Stage 2	Specimen development to ensure correct failure mode and order of life.	(1) Low load transfer (LLT) (2) High load transfer (HLT) (a) Double shear (no secondary bending) (b) With secondary bending.
	Assessment	Confirms design of specimens, nature of loading and 'Basic Programme' conditions.
Stage 3	'Basic Programme' of tests on seven fasteners selected under Stage 1.	Test five samples of each of two specimen types at two stress levels.
	Assessment	Select up to four fasteners for test under more variables (as Stage 4) from results.
Stage 4	To evaluate significance of variables. Five specimens for each condition.	4.1 Plate material 4.2 Plate thickness 4.3 Fastener material 4.4 Fastener diameter 4.5 Interfay 4.6 Fastener head shape 4.7 Loading spectrum 4.8 Initial crack in plate 4.9 Constant amplitude test 4.10 Secondary bending
	Assessment	To consider effect of variables shown by Stage 4, plan more tests if required.
Stage 5	To check interaction of effects studies in Stage 4.	Combinations of parameters 4.1 to 4.6 will be tested to assess the fatigue life prediction model developed in this Stage.
Stage 6	To present results.	Publish results to show quality and relative merit of fasteners tested under various conditions, and give guidance on performance prediction or evaluation by test of other types of fastener.

Table 8

(a) Typical chemical composition and mechanical properties of 7010-T7651

Chemical composition - unclad

	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Zr	Cr
% Min	1.5	2.2	-	-	-	-	5.7	-	-	-	0.11	-
% Max	2.0	2.7	0.1	0.15	0.3	0.05	6.7	0.05	0.05	0.05	0.17	0.05

Remainder Al

Mechanical properties - minimum requirements - L direction

Tensile strength	- 530 MPa
0.2% proof stress	- 450 MPa
Elongation % gauge length 50 mm	- 8

(b) Typical chemical composition and mechanical properties of 7050-T76

Chemical composition - unclad

	Cu	Mg	Si	Fe	Mn	Zn	Ti	Zr	Cr
% Min	2.00	1.9	-	-	-	5.70	-	0.08	-
% Max	2.60	2.6	0.12	0.15	0.10	6.70	0.06	0.15	0.04

Remainder Al

Mechanical properties - L direction

	Min	Max
Tensile strength (MPa)	573	592
0.2% proof stress (MPa)	521	552
Elongation % gauge length 50 mm	12	12.5

Table 9

FATIGUE ENDURANCE OF LOW-LOAD-TRANSFER JOINTS

Fastener system	FALSTAFF flights to failure and $\boxed{\text{log mean}}$ values at peak applied net section stress			
	280 MPa		350 MPa	
	Specimen No.	Flights	Specimen No.	Flights
Hi-Lok (Datum)	L1/11	25231	L1/4	6631
	L1/12	12372	L1/5	5711
	L1/13	21359	CL1	4929
	L1/14	19292		
		$\boxed{18938}$		$\boxed{5715}$
Huck-Crimp	L5/3	12929	L5/1	5280
	L5/4	10724	L5/2	5698
	L5/6	13172	L5/8	6128
	L5/7	11011	L5/9	5024
	L5/5	18959	L5/10	5024
		$\boxed{13069}$		$\boxed{5414}$
Hi-Tigue	L4/1	55351	L4/6	17080
	L4/9	54772	L4/3	17729
	L4/4	53172	L4/8	22959
	L4/7	42172	L4/5	21572
	L4/10	74772	L4/2	23372
		$\boxed{55109}$		$\boxed{20368}$
Taper-Lok	L2/6	54231	L2/2	22972
	L2/7	37772	L2/4	30796
	L2/3	50631	L2/1	14224
	L2/8	24831	L2/9	27172
	L2/10	27863	L2/5	26811
		$\boxed{37254}$		$\boxed{23606}$

Table 9 (concluded)

Fastener system	FALSTAFF flights to failure and $\boxed{\text{log mean}}$ values at peak applied net section stress			
	280 MPa		350 MPa	
	Specimen No.	Flights	Specimen No.	Flights
FTI Split Sleeve with Hi-Lok	L6/2 L6/3 L6/5 L6/6 L6/8	72372 82172 40529 43372 60572 $\boxed{57585}$	L6/1 L6/7 L6/4 L6/10 L6/9	14725 20711 18031 23359 16559 $\boxed{18431}$
Acres Sleeve with Hi-Lok	L7/4 L7/5 L7/6 L7/7 L7/9	54625 34372 60511 38231 44231 $\boxed{45364}$	L7/1 L7/2 L7/3 L7/8 L7/10	19372 17031 21231 22989 19972 $\boxed{20020}$
Huck-EXL	L3/1 L3/2 L3/4 L3/6 L3/7	27531 80280 120272 39759 36431 $\boxed{52132}$	L3/3 L3/5 L3/8 L3/9 L3/10	14224 20631 26490 39111 24205 $\boxed{23625}$

Table 10

FATIGUE ENDURANCES OF DOUBLE-SHEAR HIGH-LOAD-TRANSFER JOINTS

Fastener system	FALSTAFF flights to failure and $\boxed{\text{log mean}}$ values at peak applied net section stress			
	280 MPa		375 MPa	
	Specimen No.	Flights	Specimen No.	Flights
Hi-Lok (Datum)	H1/1	37898	H1/2	7572
	H1/6	23172	H1/9	4031
	H1/5	30839	H1/8	3559
	H1/10	34929	H1/3	3431
	H1/7	14821	H1/4	2959
		$\boxed{26875}$		$\boxed{4060}$
Huck-Crimp	H5/7	50911	H5/1	18943
	H5/3	14825	H5/5	14329
	H5/8	45274	H5/10	17031
	H5/2	143431	H5/4	20572
	H5/6	114529	H5/9	19524
		$\boxed{56214}$		$\boxed{17937}$
Hi-Tigue	H4/2	66624	H4/1	34224
	H4/5	32796	H4/3	27749
	H4/7	52172	H4/4	27031
	H4/9	123227	H4/6	12972
	H4/10	41024	H4/8	20924
		$\boxed{56510}$		$\boxed{23368}$
Taper-Lok	H2/3	172929	H2/8	21421
	H2/6	-	H2/5	-
	H2/1	91211	H2/2	42929
	H2/9	191085	H2/10	29206
	H2/7	134759	H2/4	47772
		$\boxed{141963}$		$\boxed{33655}$

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Table 10 (concluded)

Fastener system	FALSTAFF flights to failure and log mean values at peak applied net section stress			
	280 MPa		375 MPa	
	Specimen No.	Flights	Specimen No.	Flights
FTI Split Sleeve with Hi-Lok	H6/2	51172	H6/7	31759
	H6/8	76759	H6/3	34525
	H6/4	<224420	H6/5	-
	H6/1	166196	H6/6	27772
	H6/9	93021	H6/10	27359
		106386		**30212**
Acres Sleeve with Hi-Lok	H7/2	124759	H7/10	13624
	H7/6	41929	H7/4	9031
	H7/7	45635	H7/5	16972
	H7/8	-	H7/9	-
	H7/1	-	H7/3	12329
			H7/12	30621
		62034		**15113**
Huck-EXL	H3/9	211711	H3/6	87511
	H3/1	155031	H3/7	58880
	H3/3	155172	H3/8	55172
	H3/4	96996	H3/10	59929
	H3/5	146572	H3/2	52972
		148580		**61814**

Table 11

SUMMARY OF FATIGUE LIVES AND LIFE IMPROVEMENT FACTORS

Fastener system	Log mean life (FALSTAFF flights) and life ratio relative to Hi-Lok datum life			
	Low-load-transfer joint (LLT)		High-load-transfer joint (DS)	
	Reference stress (MN/m^2)		Reference stress (MN/m^2)	
	280	350	280	375
Hi-Lok	18938 1	5715 1	26875 1	4060 1
Huck-crimp	13069 0.69	5414 0.95	57898 2.15	18040 4.44
Hi-Tigue	55109 2.91	20368 3.56	56494 2.1	23368 5.76
Taper-lok	37254 1.97	23606 4.13	141963 5.28	33656 8.29
FTI Split Sleeve + Hi-Lok	57587 3.04	18431 3.22	106386 3.96	30212 7.44
Acres Sleeve + Hi-Lok	45343 2.39	20020 3.50	62133 2.31	15113 3.72
Huck-EXL	48835 2.58	23625 4.13	148579 5.53	61814 15.23

Reference stress (based on net area) is the maximum stress in the FALSTAFF sequence.

Table 12

FATIGUE ENDURANCES OF LOW-LOAD-TRANSFER CORE PROGRAMME SPECIMENS

Fastener system	FALSTAFF flights to failure and $\boxed{\text{log mean}}$ values at peak applied net section stress			
	280 MPa		350 MPa	
	Specimen number	Flights	Specimen number	Flights
Hi-Lok in Plain hole	A2	26337	A1	6221
	A4	19972	A5	7031
	A8	21724	A6	6031
	A9	24129	A7	4480
	A10	23172	A11	4729
		$\boxed{22966}$		$\boxed{5616}$
FTI Split Sleeve with Hi-Lok	CW2	136464	CW1	19172
	CW3	173572	CW4	33880
	CW7	50759	CW5	32031
	CW8	178745	CW6	22329
	CW9	240231	CW10	39824
		$\boxed{138859}$		$\boxed{28408}$

Table 13

FATIGUE ENDURANCES OF SINGLE-SHEAR HIGH-LOAD-TRANSFER PROGRAMME SPECIMENS

Fastener system	FALSTAFF flights to failure and $\boxed{\text{log mean}}$ values at peak applied net section stress			
	280 MPa		350 MPa	
	Specimen number	Flights	Specimen number	Flights
Hi-Lok in plain hole	X3 X4 X7 X9 X10	12128 14431 12160 13831 14031 $\boxed{13280}$	X1 X2 X5 X6 X8	3925 2929 3444 4336 - $\boxed{3639}$
FTI Split Sleeve with Hi-Lok	CW2 CW4 CW6 CW9 CW10	9631 12424 12329 16224 17361 $\boxed{13337}$	CW1 CW3 CW5 CW7 CW8	- 3801 3172 3624 5323 $\boxed{3905}$

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Table 14

LOAD TRANSFER (LT) AND SECONDARY BENDING (SB) MEASUREMENTS FOR Q-JOINTS WITH HI-LOK FASTENERS IN (a) PLAIN AND (b) COLD EXPANDED HOLES

% of the max load in FALSTAFF	Type (a)		Type (b)	
	LT %	SB ratio	LT %	SB ratio
0	0		0	0
16.7	30.4	0.192	28.0	0.264
33.3	36.1	0.341	37.5	0.297
50.0	41.3	0.350	42.3	0.353
66.7	44.3	0.376	44.9	0.393
83.3	46.4	0.405	47.3	0.422
100.0	49.6	0.443	48.7	0.441
83.3	51.3	0.406	49.8	0.402
66.7	52.5	0.348	50.3	0.352
50.0	54.5	0.318	51.3	0.302
33.3	56.8	0.309	53.3	0.270
16.7	65.3	0.336	59.3	0.327
0	0	0	0	0
Minimum load	48.3	0.418	52.0	0.290
0	0	0	0	0

Max load (kN): 67
Min load (kN): -20.5

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9	H. Huth	The influence of fastener flexibility on load transfer and fatigue life prediction for multi-row bolted and riveted joints. RAE Library Translation 2132 (1985) of LBF Report FB-172 (1984)

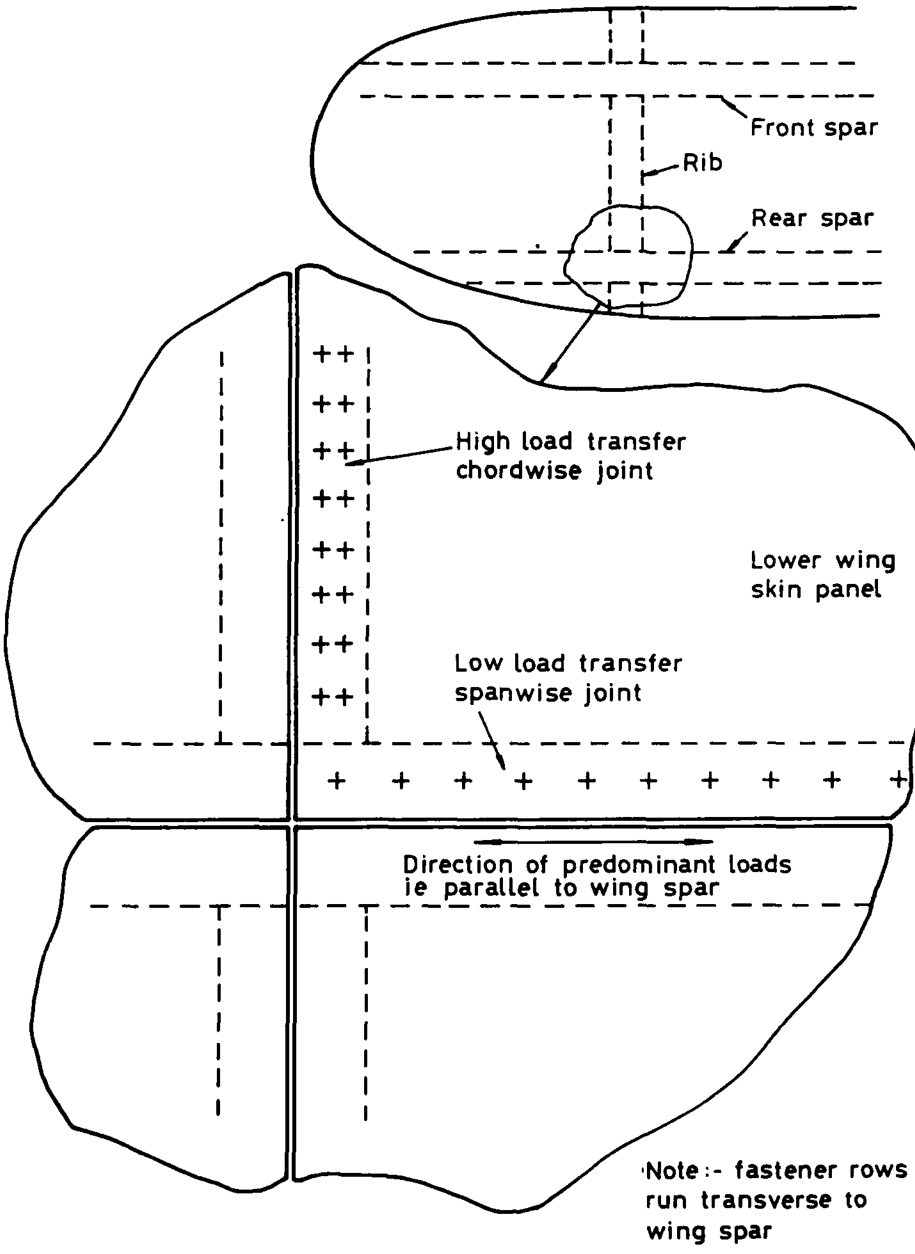

Fig 1 Typical fastener distributions in lower wing skin connection

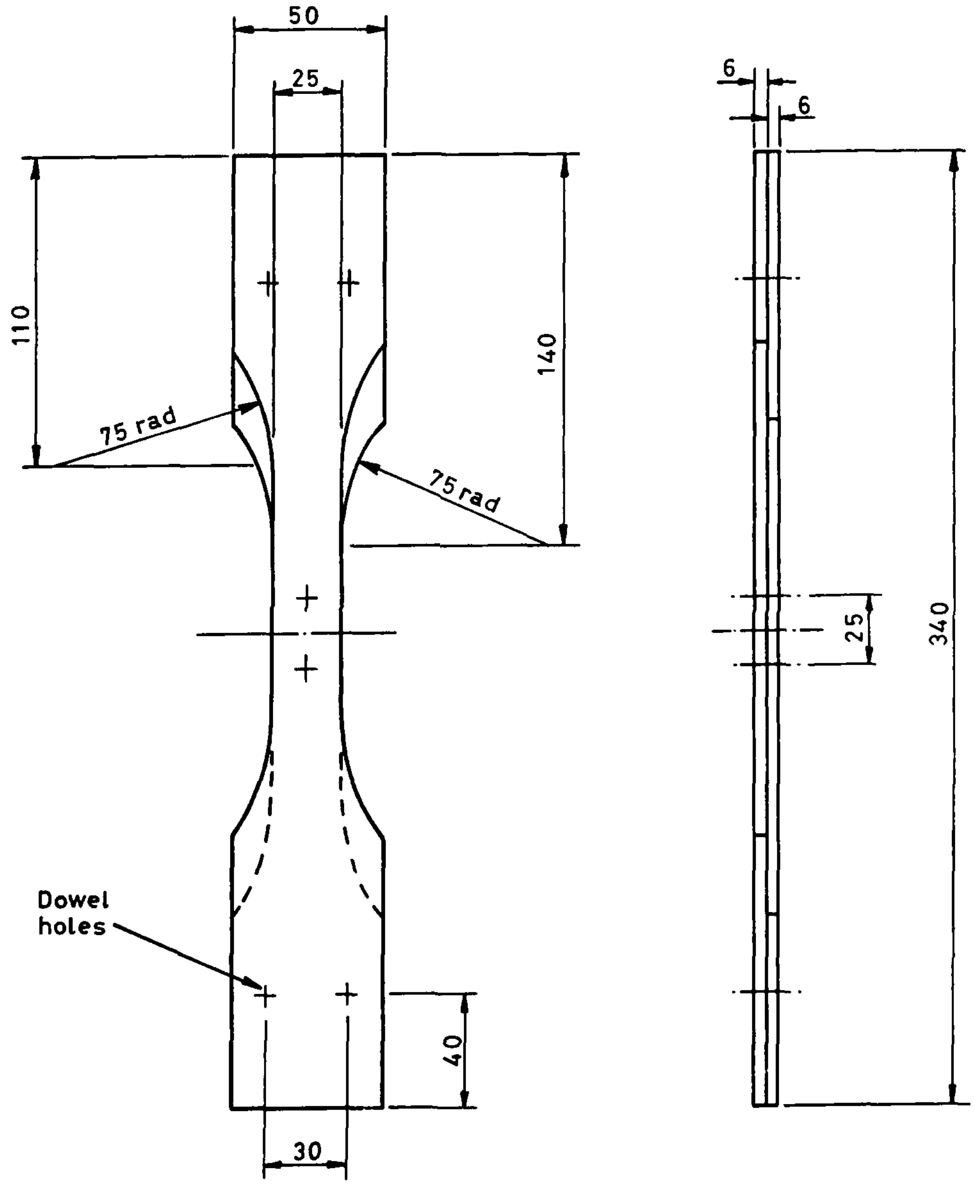

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Fig 2 UK low-load-transfer joint

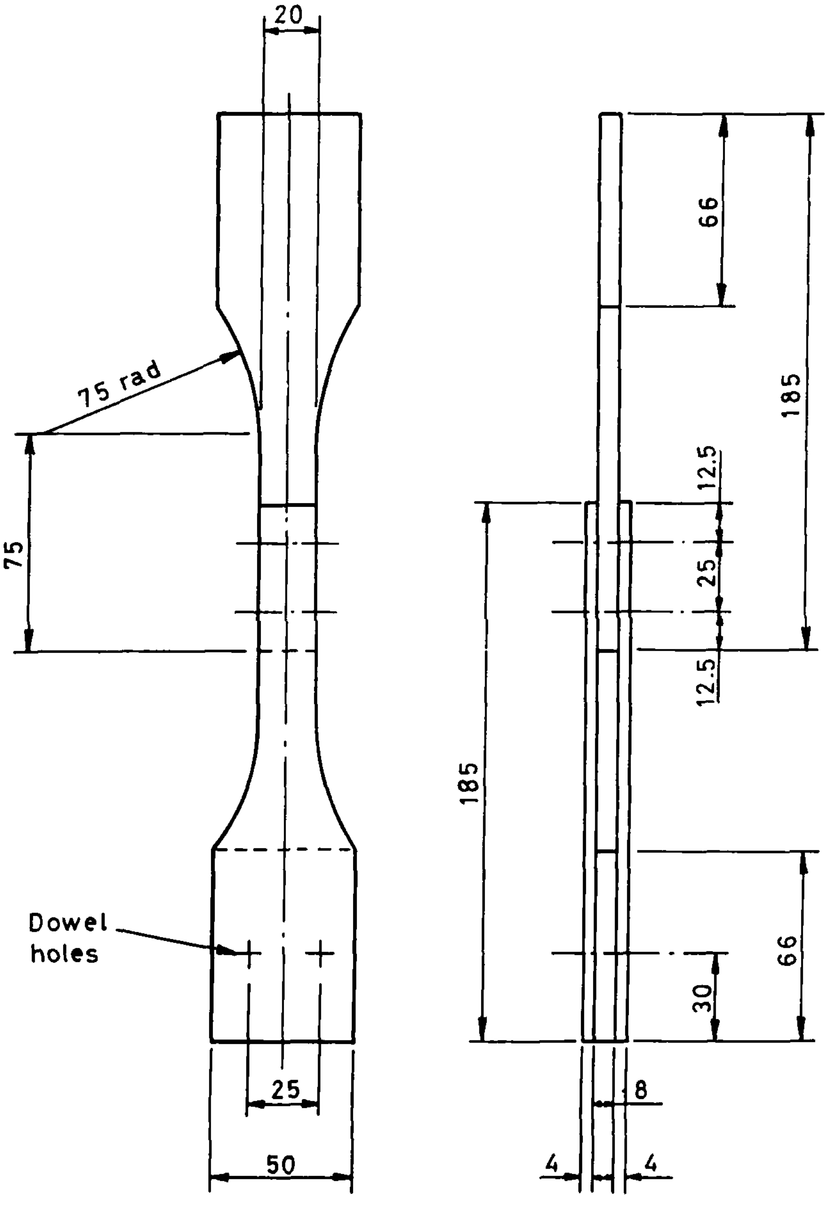

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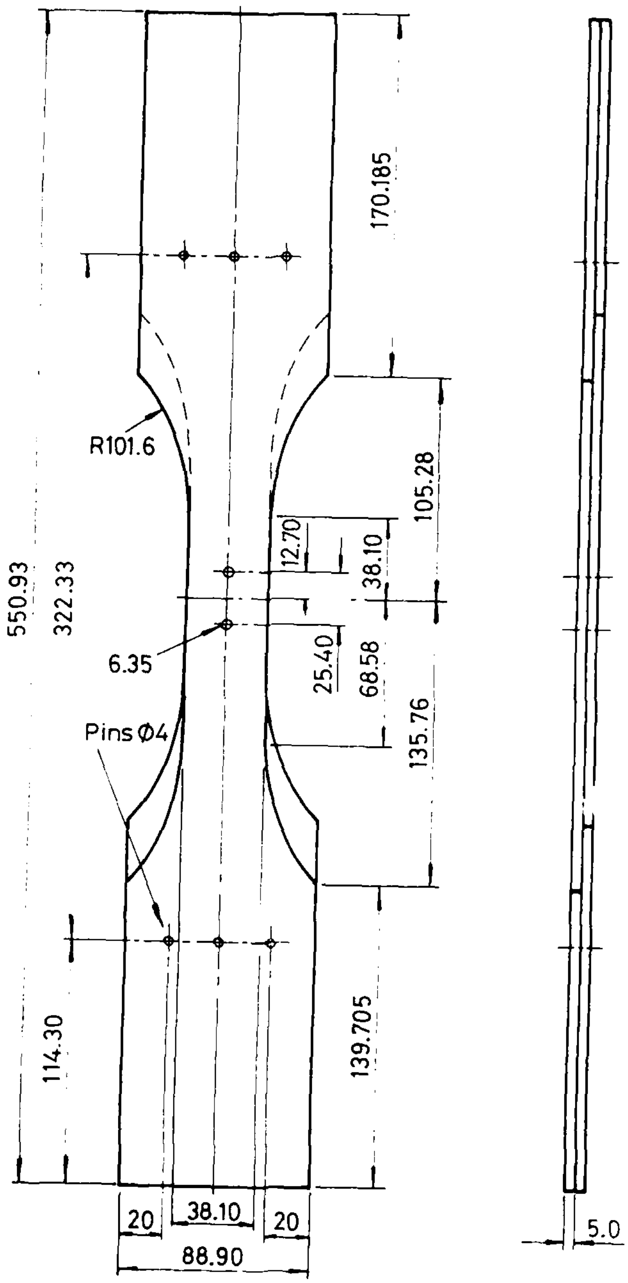
Fig 3 Double-shear high-load-transfer joint



Dimensions in mm

Fig 4 AGARD low-load-transfer joint

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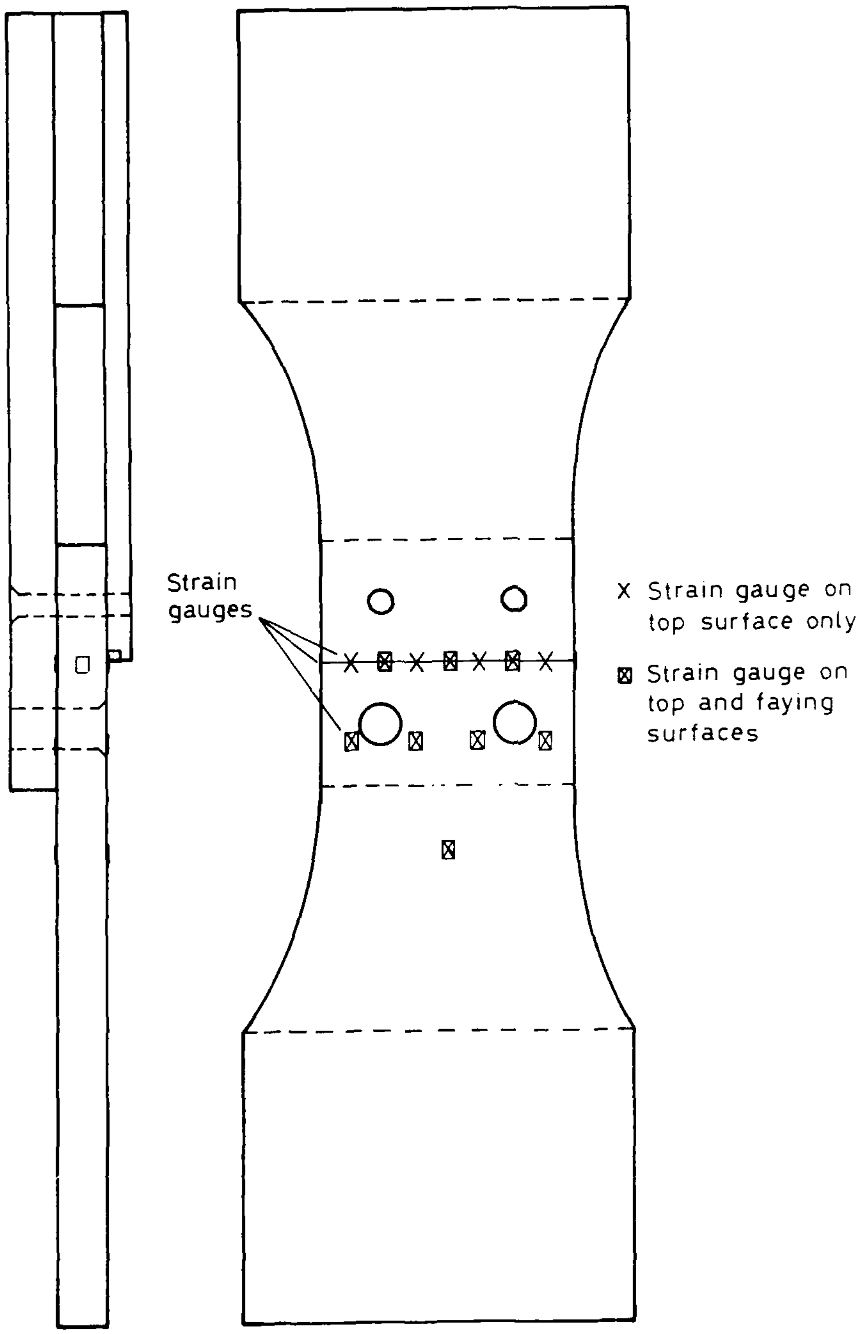
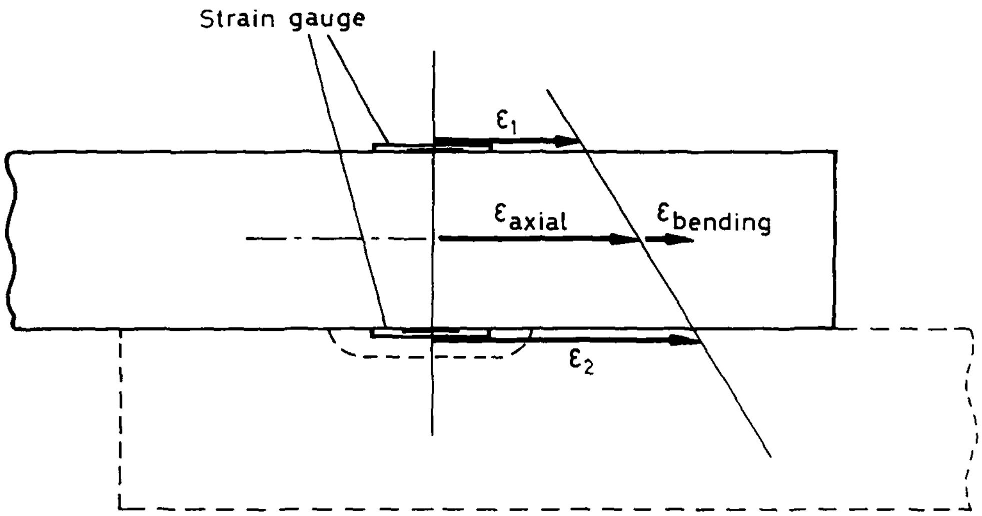
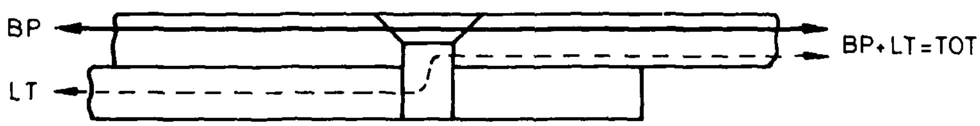


Fig 5 Strain gauge positions on Q-joint

Fig 6



$$\text{Secondary bonding ratio} = \frac{\varepsilon_{bending}}{\varepsilon_{axial}}$$



BP = bypass load
LT = load transfer
TOT= total load

$$\text{\% load transfer} = \frac{LT}{TOT} \times 100\%$$

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Fig 6 Definition of load transfer and secondary bending

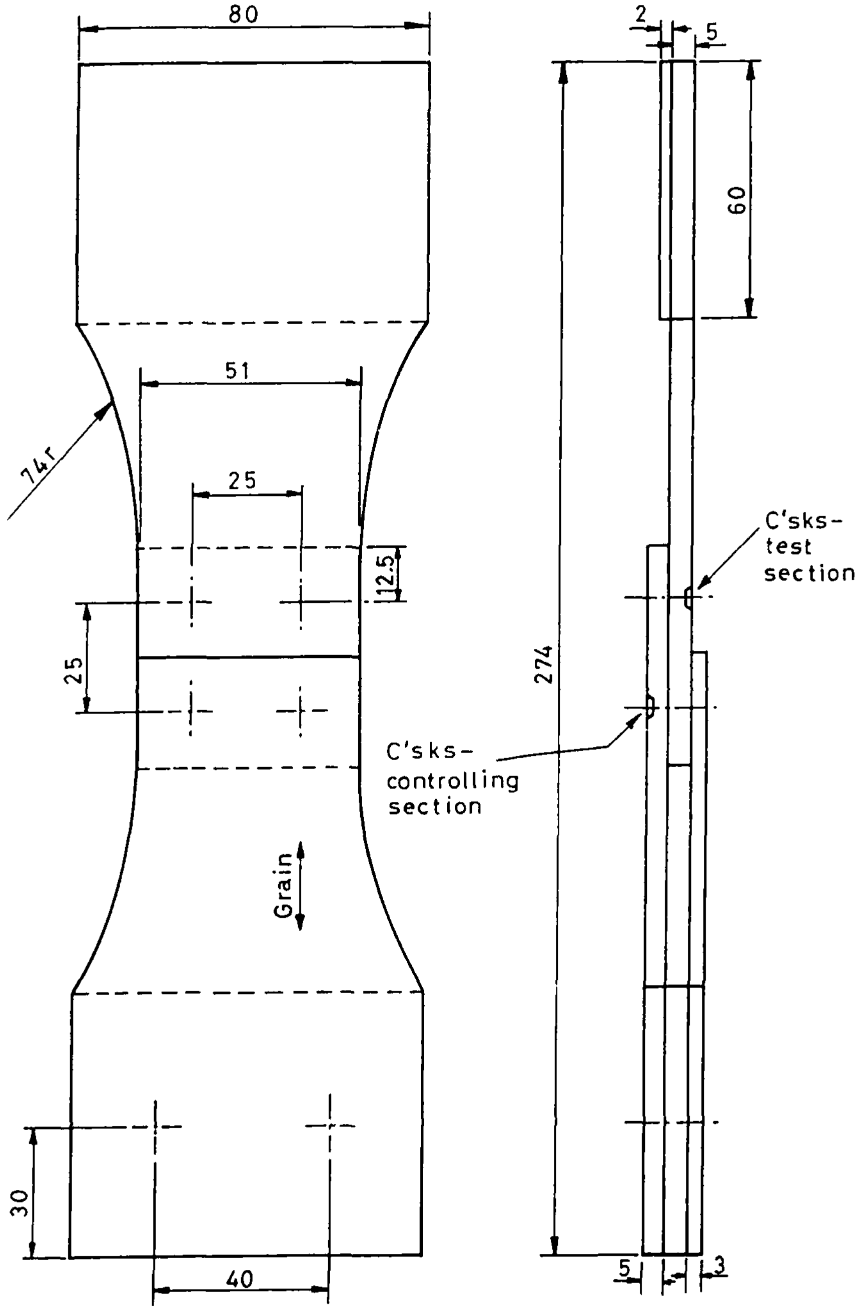

Fig 7 Q-joint for single-shear high-load-transfer joint programme

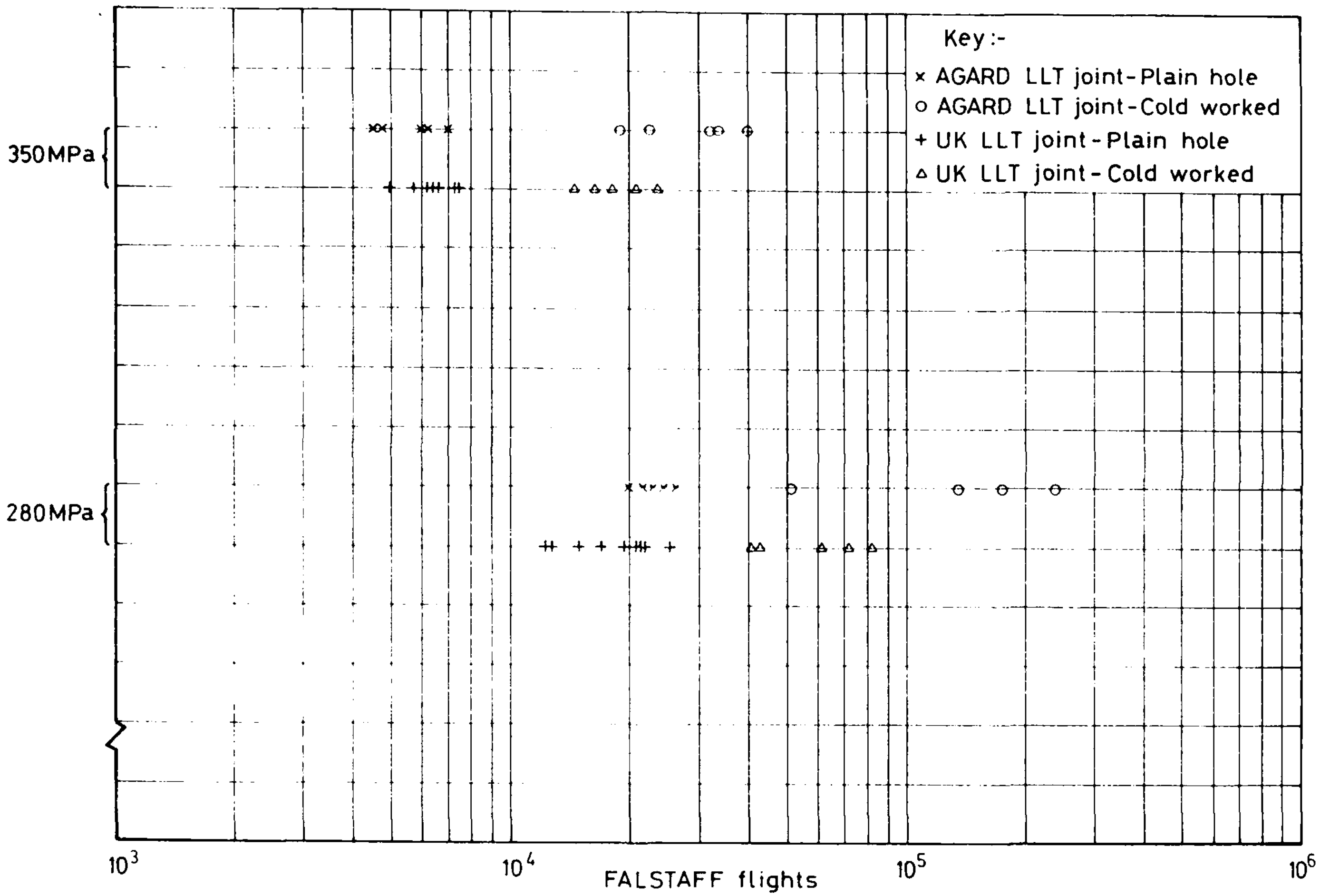

Fig 8 Fatigue lives of AGARD and UK low-load-transfer joints

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

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15. Distribution statement

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(b) Special limitations (if any) –

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Fatigue. Fastener. Interference fit. Cold expansion. Joint.

17. Abstract

This Report describes an investigation of the relative merits of a number of fastener systems. They are termed 'fatigue-rated' fastener systems since they aim to enhance the fatigue endurance of the surrounding structure. Fatigue tests were performed on a number of laboratory specimens which simulated bolted connections in aircraft wing structures. It was shown that fastener systems incorporating hole cold expansion or fasteners installed with high interference fits were significantly superior to fasteners installed with a clearance fit in plain holes under the same test conditions. The longest fatigue endurances were observed in joints which contained fastener systems incorporating both cold expansion and a high degree of fastener interference. It was noted however that cold expansion of fastener holes in asymmetric joints, with induced bending stresses, gave no increase in fatigue endurance over joints with fasteners installed in plain holes.

The work was carried out as part of an international collaborative exercise co-ordinated through the Structures and Materials Panel of AGARD.

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